APRIL 1953

Chemical Engineering Progress

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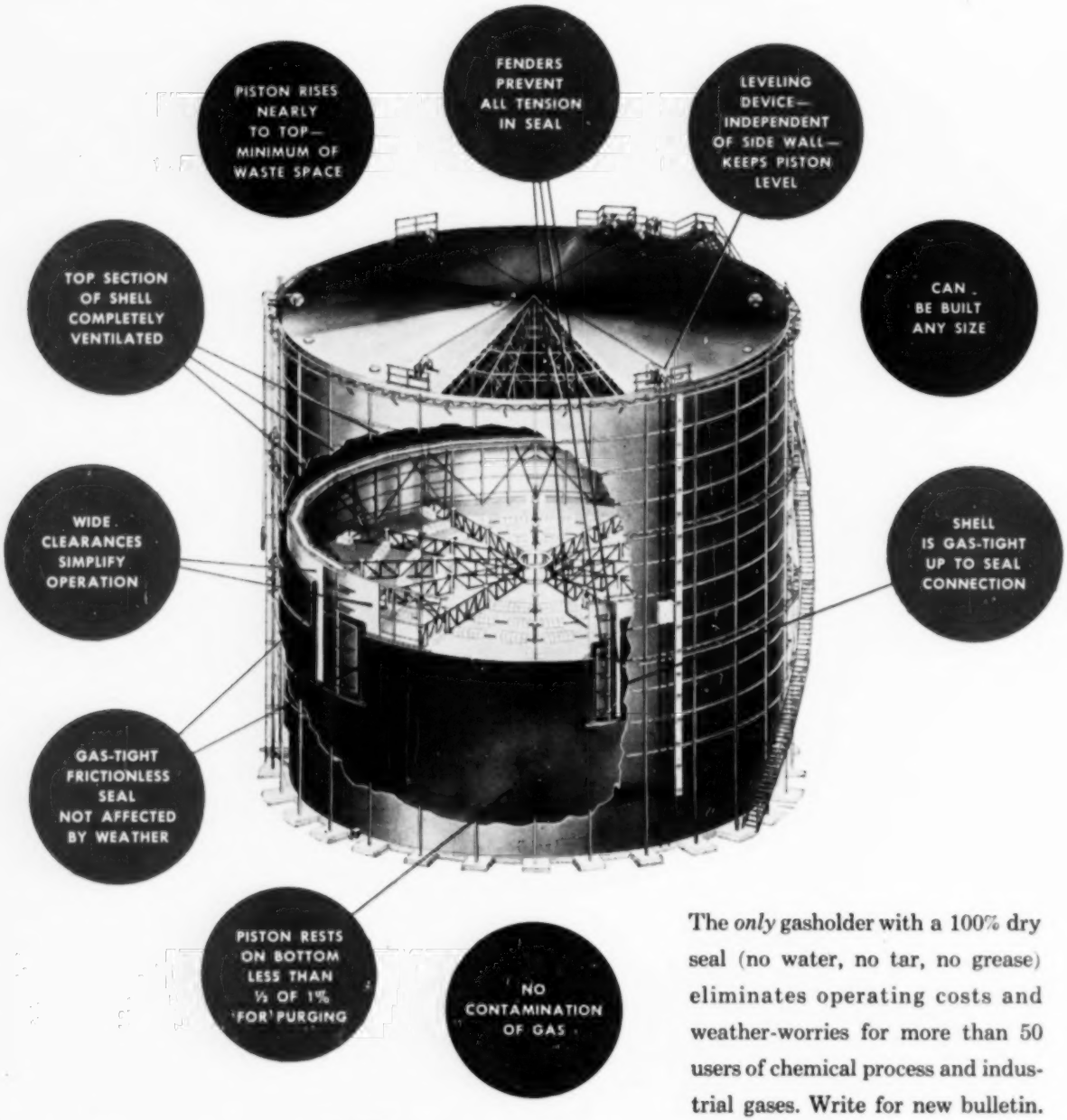
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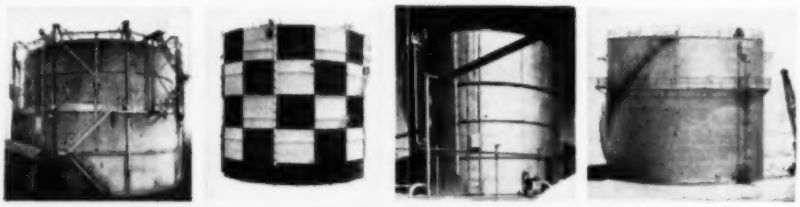

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Chemical Engineering Progress

APRIL, 1953

Volume 49, Number 4

Editor: *F. J. Van Antwerpen*

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for modern ways
to handle old problems,
specify Fischer & Porter
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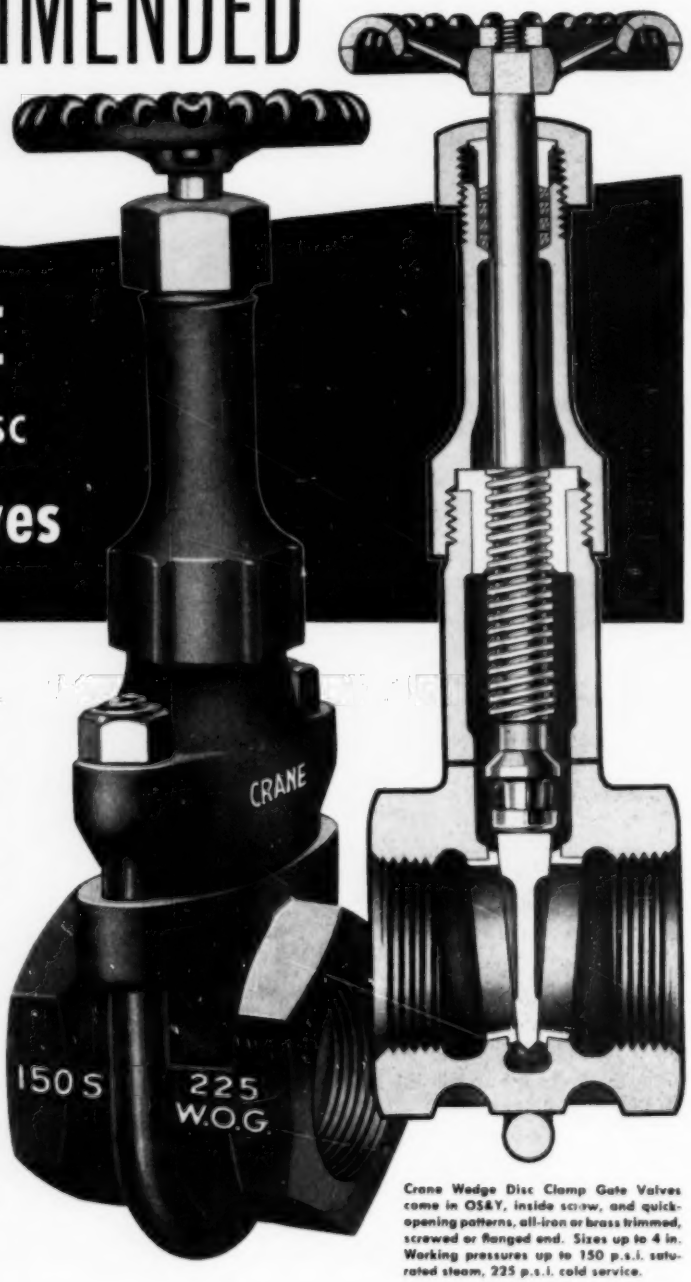

Crane Wedge Disc Clamp Gate Valves come in OS&Y, inside screw, and quick-opening patterns, all-iron or brass trimmed, screwed or flanged end. Sizes up to 4 in. Working pressures up to 150 p.s.i. saturated steam, 225 p.s.i. cold service.

Low in first cost, as well as in upkeep . . . and look at their wide utility—

Use Crane Clamp Gate Valves for steam; hot and cold water; crude, fuel, and lubricating oil; air, gas, and gasoline service.

Also in food and chemical process industries for caustic solutions, alkalies, corrosive chemicals, and gases.

You'll find Crane Clamp Gate Valves extra rugged, with a strong reinforced body and husky stem. Their compact design means a better fit for more places . . . a saving on piping in many cases. And because of the simplified clamp construction, these valves enjoy wide favor where frequent cleanout is essential. The bonnet assembly and wedge disc lift out easily—the body stays in the line. Reassembling is no problem—the bonnet joint makes up tight and stays tight.

Wide choice of regular patterns, all-iron or brass trimmed. On inside screw all-iron valves, an improved self-draining bonnet prevents entrapment of line fluids in the bonnet—protects the threads, keeps the stem working smoothly. Send for Folder AD 1667 or ask your Crane Representative for full details.

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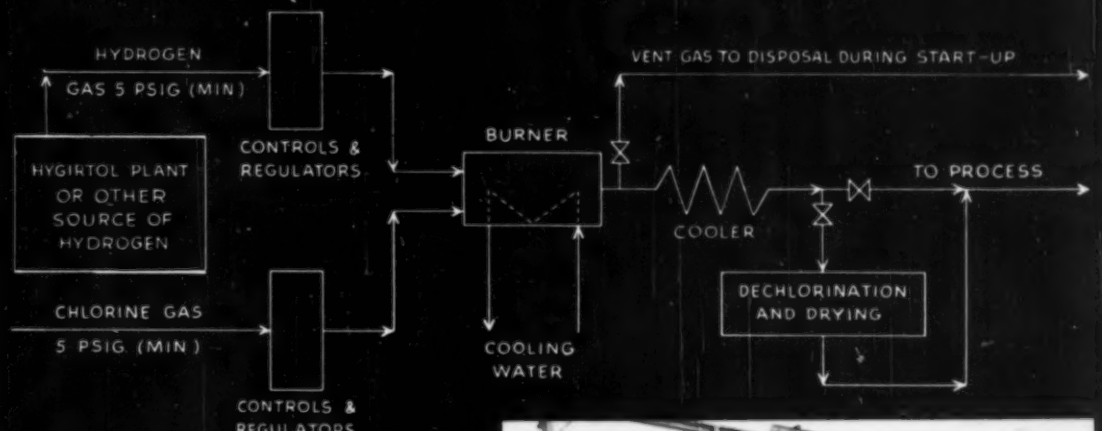

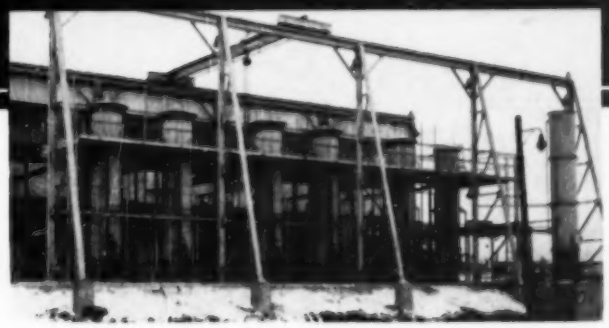

...Girdler designs and builds the plant

THE GIRDLER CORPORATION is a licensing agent for the hydrogen chloride manufacturing process developed by Hooker Electrochemical Co. Girdler designs, builds, and licenses these plants for the production of anhydrous hydrogen chloride from hydrogen and chlorine. The process has proved to be highly efficient, low in maintenance and to give uniformly good yields.

Girdler gas processing plants for many products and problems serve the outstanding companies of the chemical field. Investigate Girdler's complete process design-engineering-construction service for *your* problems. Call the nearby Girdler office today.

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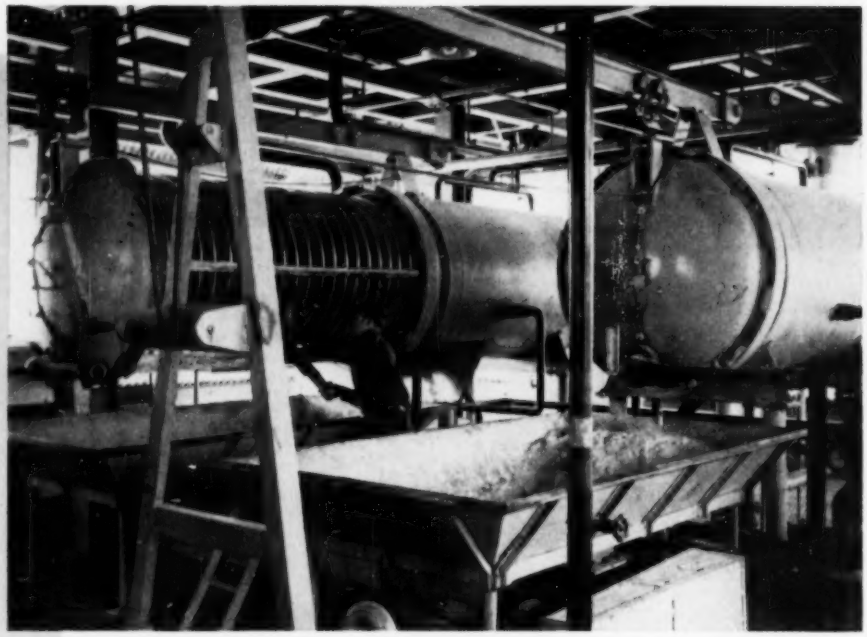

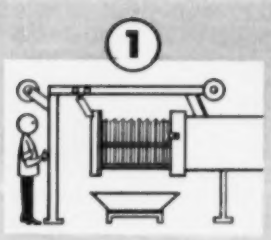

One motion unlocks the quick-opening filter cover. The all-metal leaves roll out of the filter as a unit.

Operator taps leaves to drop cake into trough, hopper or wagon for recovery or disposal.

Then he returns clean leaves into filter. The cover locks pressure-tight with one swift motion.

Large-capacity filter

is easy to clean between cycles

One man can open this filter, dump the cake from it, and close it again—in about ten minutes!

That's one reason why the Niagara Style "H" Filter can cut your costs on large liquid filtration and solids recovery applications.

Niagara can now offer you both vertical and horizontal pressure-leaf filters, with unit sizes from 20 to 1500 square feet. If you are a big user of filtration, you'll want all the facts on what these filters can do for you. Just write or mail the coupon today.

LARGE CAPACITY—The Style "H" Filter delivers high-clarity filtrate at rates up to 45,000 GPH. Sizes range up to 1500 sq. ft. of working filter area in one compact, leak-proof unit.

ALLOY CONSTRUCTION—AT LOWER COST—Because of its simple fabricated design, you can have the Niagara Filter in stainless steel and other alloys, for corrosion resistance, at low cost. Special linings are available, too.

EXCELLENT CAKE-WASHING CHARACTERISTICS—Almost true displacement washing.

JACKETING IS NO PROBLEM, EITHER—The filter shell can be readily jacketed for heating or cooling at minimum additional cost.

LOW DAY-TO-DAY COST—Tending the filter is a part-time job for one man. The all-metal leaves rarely require cloths—another big saving.

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Engineering and Sales Office: 3087 Main St., Buffalo 14, N. Y.
(When writing, please use above address)
Factory: East Moline, Illinois
IN EUROPE: Niagara Filters Europe, 36 Leidsegracht, Amsterdam-C, Holland

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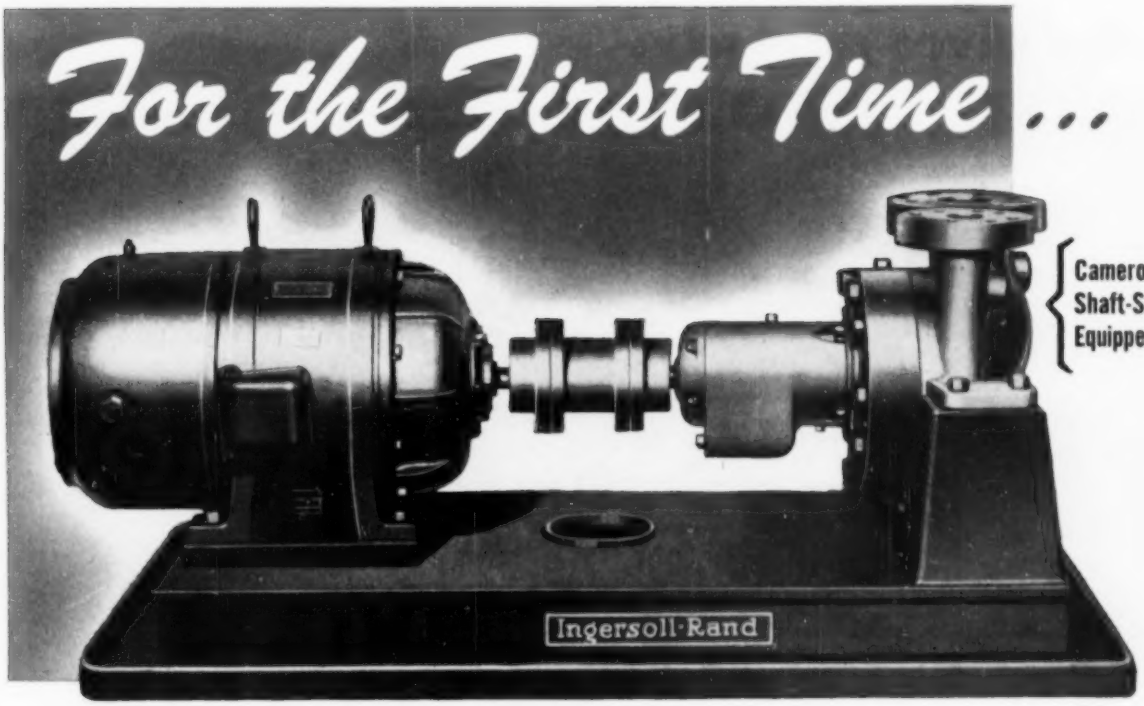
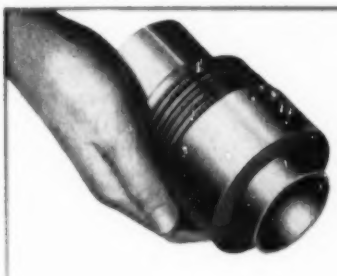


A REFINERY AND PROCESS PUMP DESIGNED AROUND A MECHANICAL SEAL



CAMERON SHAFT-SEAL
The answer to tough stuffing box problems.

A stationary sealing face of carbon and a rotating seal ring of stellited steel constitute the heart of the Cameron Shaft-Seal. Balanced sealing areas control contact pressure between the sealing faces, effectively preventing leakage without undue wear of the rotating fit. In difficult sealing jobs, the Shaft-Seal succeeds where complicated packed stuffing box arrangements have failed.

Built-in Cameron Mechanical Shaft-Seal reduces liquid losses and stuffing box maintenance in this SFLA pump line!

The Cameron Shaft-Seal is an Ingersoll-Rand development that has demonstrated its dependability in thousands of process installations the world over since its introduction in 1928. Now, this same Shaft-Seal is built-in as an integral part of these pumps—*at no extra cost*. Use of the Shaft-Seal efficiently stops liquid losses and reduces stuffing box attention to a minimum.

Designed for handling light refinery liquids at moderate temperatures, SFLA-MFLA-HFLA pumps are built in five sizes from 1 to 4 inches for low, medium and high head applications. Top discharge is standard, with top or end suction nozzles available. Capacities to 1000 gpm and pressures to 600 psi. Write, or ask your Ingersoll-Rand representative for full details.

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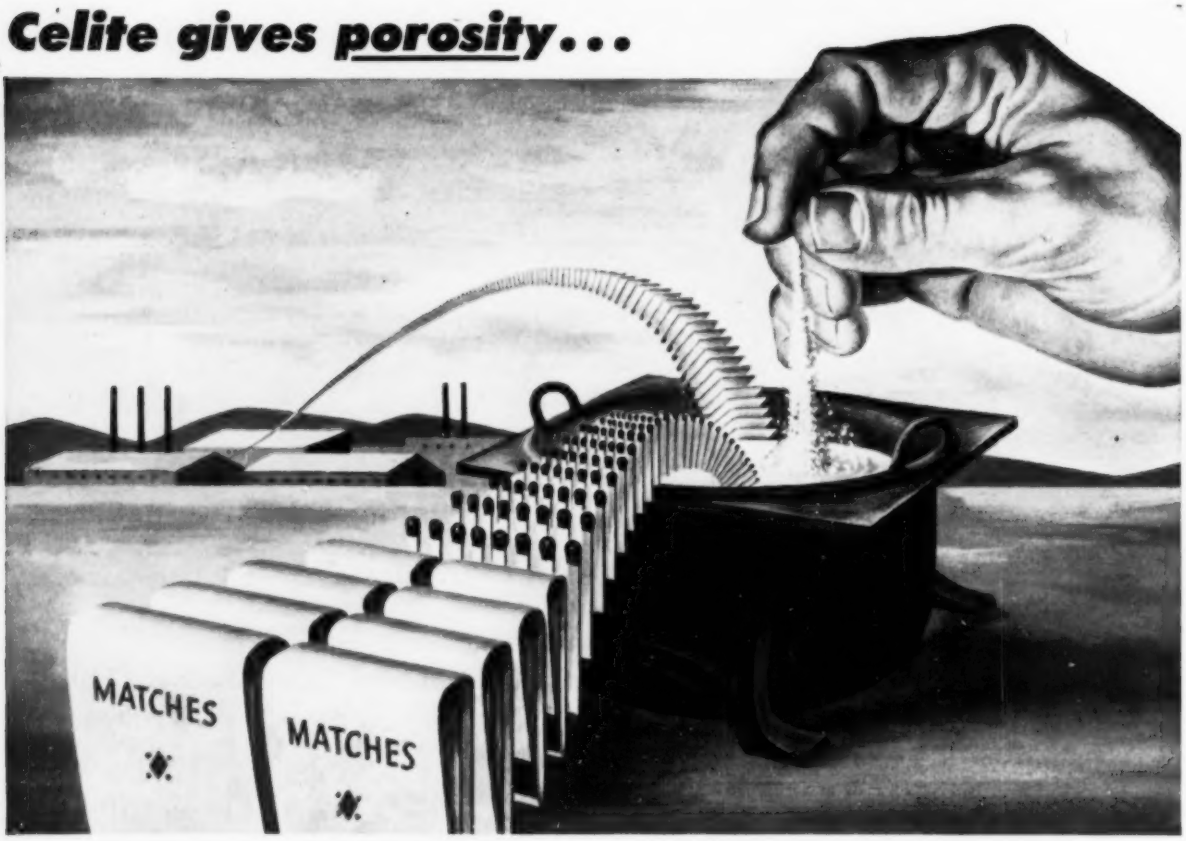

Adding "Safety Valves" to match heads

Incorporated in match heads, Celite Mineral Fillers act as "safety valves" to prevent flare-up and kill afterglow.

The explanation: *Celite's porous, thin-walled, cellular structure gives the match heads greater porosity so that gas can escape quickly.*

Celite's abrasive quality also makes matches easier to strike. And from a production line standpoint, the high absorptive capacity of this mineral filler speeds drying of the match heads . . . while its light weight and great bulk improve dispersion of the active chemicals in the match head mix.

These and other unusual physical characteristics adapt Celite Mineral Fillers to numerous industrial uses.

THESE CELITE PROPERTIES BENEFIT MANY TYPES OF PRODUCTS

Celite's minute, chemically inert particles have an irregular, spiny structure—which accounts for their efficiency as a delicate abrasive in polishes, as a flatting agent in paints, varnishes and lacquers, and as a reinforcing agent for paint films and rubber products.

Celite powders can absorb up to three times their own weight of liquid—making them particularly useful in preventing ammonium nitrate crystals from caking, in absorbing liquid insecticide poisons, and in controlling pitch trouble at paper mills. And because the loose weight of Celite averages only 10 pounds per cubic foot—these mineral fillers are employed to fluff-up insecticide dusts and household cleansers, as well as to extend white pigments in paper manufacture.

If you are looking for the "extra something" to lift your product above competition—at no extra cost—why not discuss your problem with a Johns-Manville Celite Engineer? For further information and samples, write Johns-Manville, Box 60, New York 16, N. Y. In Canada: 199 Bay Street, Toronto 1, Ontario.

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- Better Suspension
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- Better Dielectric Properties
- More Durable Finish
- Increased Viscosity
- Elimination of Caking
- Higher Melting Point
- Better Dry Mixing
- Improved Dispersion
- Greater Porosity

JOHNS-MANVILLE JM PRODUCTS

Johns-Manville CELITE®

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Here's how MANY INDUSTRIES make BETTER PRODUCTS at LOWER COST with *Buflovak Equipment*

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To assist you in the solution of processing problems, BUFLOVAK offers the facilities of its Research and Testing Laboratory . . . where small scale experimental units show you, before you buy, the commercial possibilities, data on production cost, and characteristics of the finished product.

BUFLOVAK Evaporators serve every industry where liquids must be concentrated.
Concentrating crystal-forming liquids is but one of the many applications.

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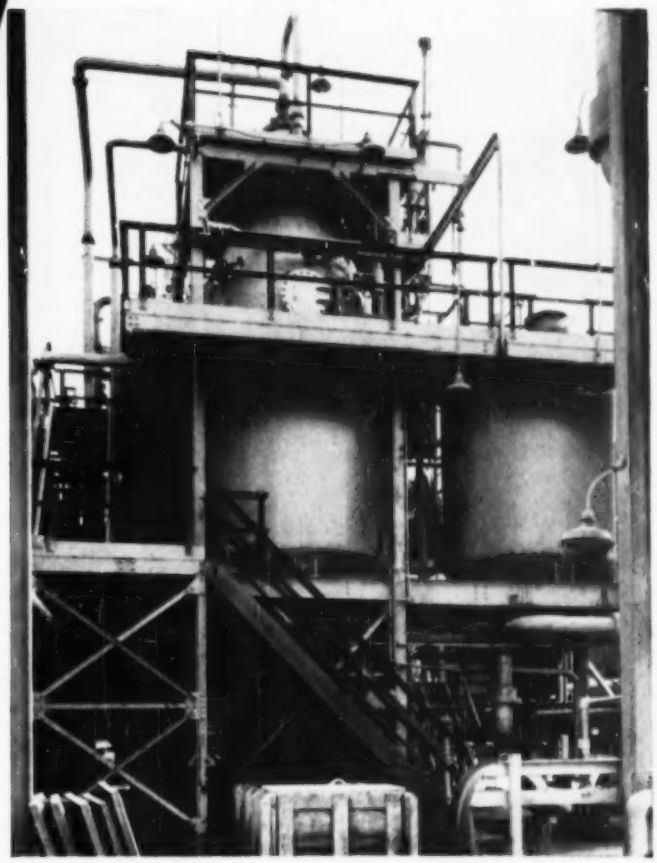
2. The production of a clear concentrate is highly important when evaporating crystal-bearing liquids or the crystal-forming liquids. BUFLOVAK Patented Crystal Classifiers simplify and improve general operating results.

3. Continuous removal of crystals. The large crystals go to the salt filter. The small crystals are returned to the evaporator where they grow to the desired size and are returned with the mother liquor to the classifier.

These units can be built separately, or as an integral part of the evaporator, for batch or continuous operation.

This BUFLOVAK Crystal Classifier, used in connection with a large Triple Effect Evaporator, plays an important part in the process of synthesizing glycerine from petroleum.



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This complete 72 page booklet on BUFLOVAK Evaporators has proved helpful to many. A request on your company letterhead will bring a copy free.

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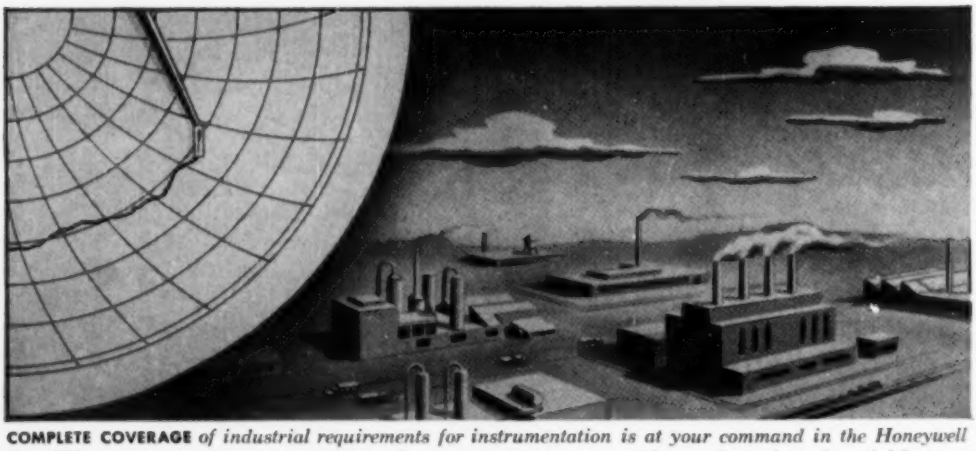
These are the building blocks of measurement and control. To combine them into systems custom-fitted to your process, Honeywell offers the know-how gained through years of experience in all branches of industry. Whether your process calls for a single instrument or a complete central control panel, you can be sure of getting the peak in performance and value . . . and the advantages of a single responsibility for the entire installation . . . when you specify *engineered instrumentation by Honeywell.*

Engineered to Lever



COMPLETE COVERAGE *of industrial requirements for instrumentation is at your command in the Honeywell line. Whatever you need to measure or control . . . to any accuracy . . . with any of a variety of special features . . . you'll find Honeywell instruments offer the most efficient solution.*

THE NEW Los Angeles plant of Lever Brothers Company utilizes the most modern methods for processing raw oils and fats into soaps, detergents and shortening. Prominent among these advanced techniques is Brown engineered instrumentation for every critical process.

In the manufacture of Spry vegetable shortening, for example, Brown instruments help to control refining, bleaching, hydrogenation and deodorizing at top output and efficiency. Companion instruments also regulate the saponification, spray drying, extrusion and other processes vital to the manufacture of toilet soaps, soap powders and detergents. Throughout the plant, Honeywell controls keep critical variables in line with the precision essential to efficient, high-volume production.

Whatever your process may be, you can be sure of getting from Brown the right instrumentation . . . properly applied. First, because the Brown line covers *every* major control requirement of the chemical industry. And second, because these instruments are custom fitted to your application by engineers who have thorough experience in process control.

control vital Brothers plant

Our local engineering representative is well qualified to recommend instrumentation for your processes . . . and he is as near as your phone.

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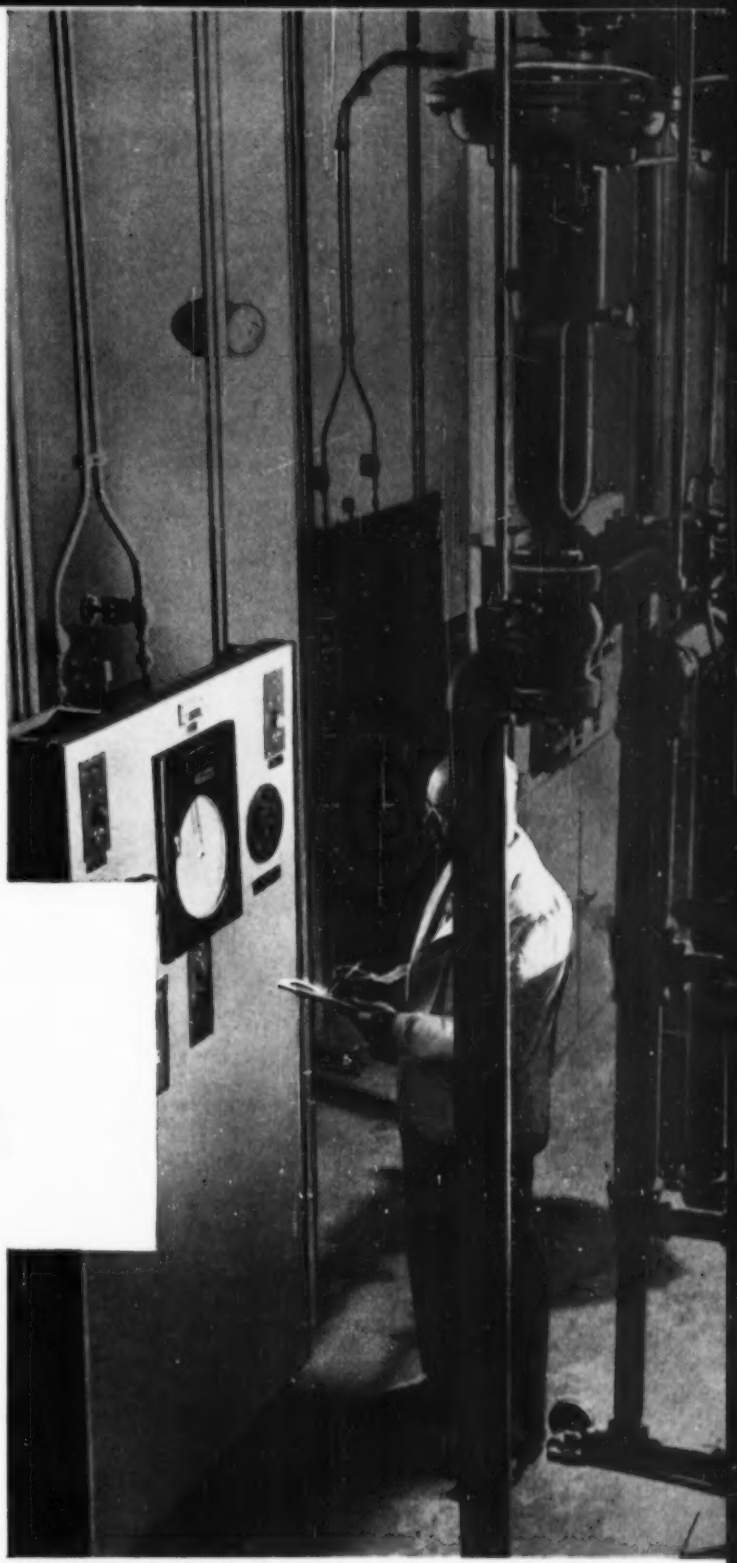
● **REFERENCE DATA:** Write for Composite Catalog No. 5000 for a condensed description of the complete Brown line.

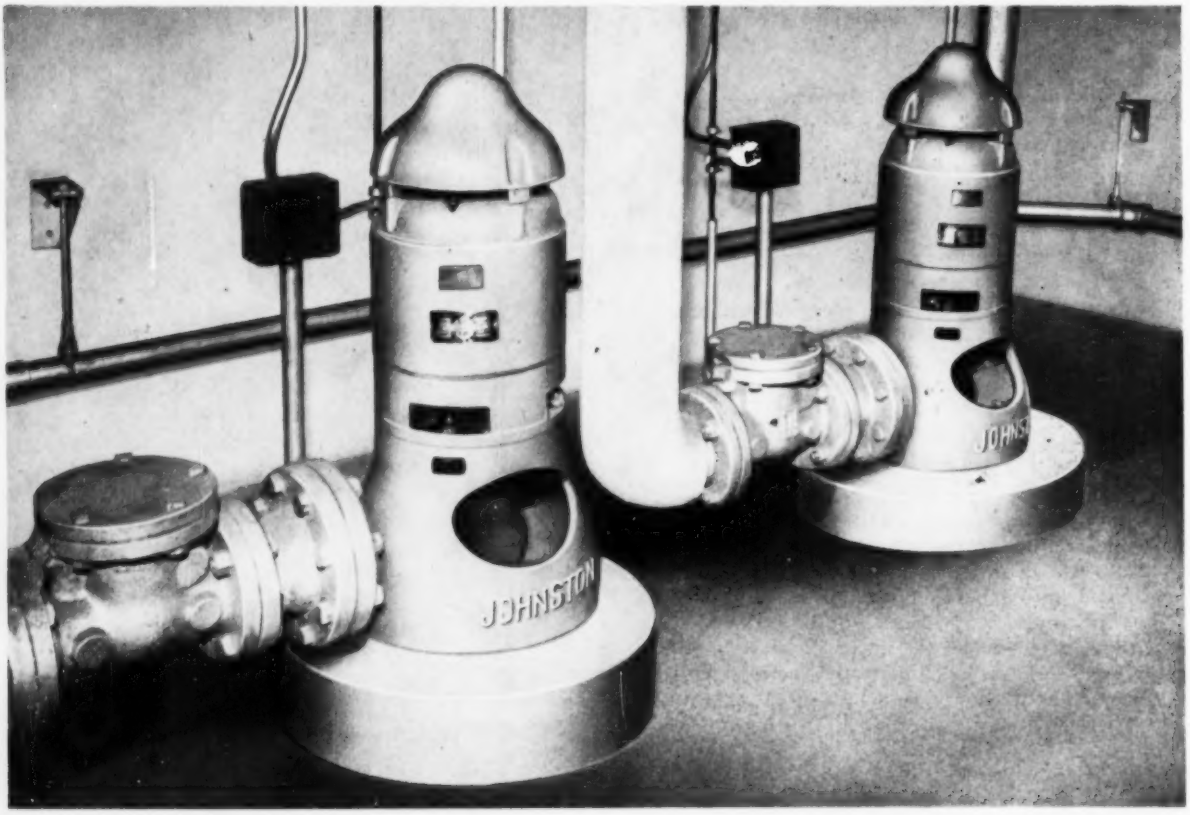


GAS FLOW *to Surf spray tower heaters is recorded by Brown Flow Meter . . . one of many in this plant. At top are Honeywell diaphragm control valves.*

MINNEAPOLIS
Honeywell
BROWN INSTRUMENTS
First in Controls

H HONEYWELL

In All Kinds of Industrial Pumping Applications



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Take this hot well installation, for example. Two Johnston Unit-Line, 3 horsepower, close-coupled pumps delivering 120 gallons per minute against a 65 foot head, were selected for this job, because . . .

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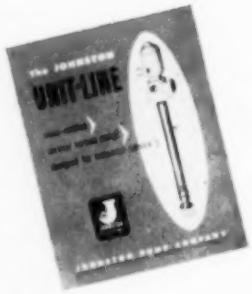
2. **NO BEARINGS TO LUBRICATE BELOW BASE LEVEL**
   Vertical, hydraulically balanced design eliminates radial thrust and consequent bearing and impeller wear.
3. **NO PRIMING NECESSARY**
   The open suction is submerged, thereby doing away with expensive priming devices used on other type pumps.

Just three of many reasons why Johnston equipment is handling all types of pumping jobs BETTER, in large or small operations. Why not let our trained engineering staff consult with you on the best solution to YOUR particular problem?



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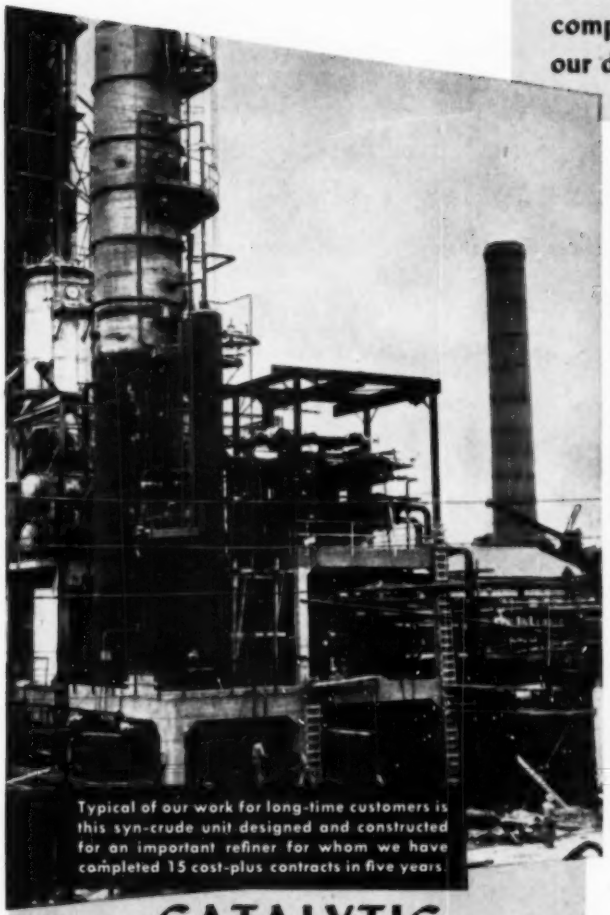

Typical of our work for long-time customers is this syn-crude unit designed and constructed for an important refiner for whom we have completed 15 cost-plus contracts in five years.

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- *Canadian Oil Refineries, Ltd., Sarnia, Ontario, Canada
- *Continental Oil Company, Ponca City, Oklahoma
- *Crown Central Petroleum Corp., Houston, Texas
- Daikyo Oil Company, Yokkaichi, Japan
- *General Electric Company, Schenectady, N. Y.
- *Gulf Oil Corporation, Pittsburgh, Pennsylvania
- *Houdry Process Corporation, Philadelphia, Pa.
- *International Minerals & Chemical Corporation, Chicago, Illinois
- *Leonard Refineries, Inc., Alma, Michigan
- Ohio Oil Company, Robinson, Illinois
- Pennsylvania Salt Mfg. Company, Philadelphia, Pa.
- *Petco Corporation, Blue Island, Illinois
- Petrol Terminal Corporation, Texas City, Texas
- Polymer Corporation, Ltd., Sarnia, Ontario, Canada
- *Pure Oil Company, Chicago, Illinois
- Pusey & Jones Corporation, Wilmington, Delaware
- *Rohm and Haas Company, Bristol, Pa.
- Shamrock Oil & Gas Corporation, Sunray, Texas
- *Sharples Chemicals Inc., Wyandotte, Michigan
- *Shaw-Kendall Company, Toledo, Ohio
- *Shell Berre Oil Company, Paris, France
- *Sinclair Refining Company, Corpus Christi, Texas
- *Socony-Vacuum Oil Company, Paulsboro, N. J.
- *Standard Oil Company of Ohio, Cleveland, Ohio
- Standard Oil Company of Texas, El Paso, Texas
- *Sun Oil Company, Philadelphia, Pa.
- Sun Oil Company, Ltd., Sarnia, Ontario, Canada
- *Susquehanna Pipe Line Company, Toledo, Ohio
- *Tide Water Associated Oil Company, Bayonne, N. J.
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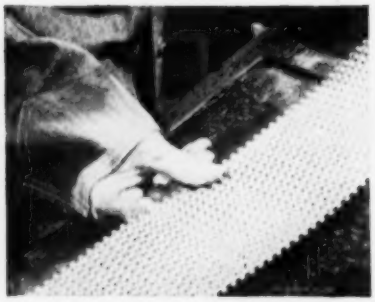
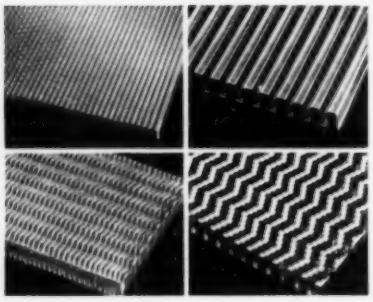
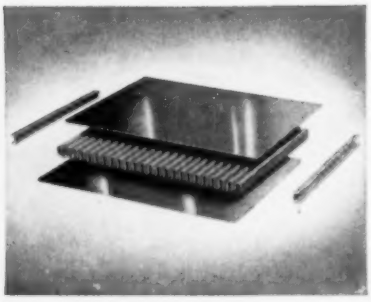


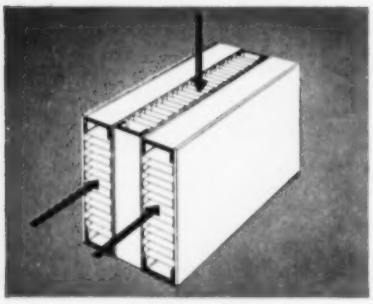
Corrugated fin surface for TRANE Brazed Aluminum Exchangers is formed in special presses from aluminum brazing sheet. Thickness can range from .005 to .032 inch; fin height to .50 inch; spacing 4 to 18 fins per inch.



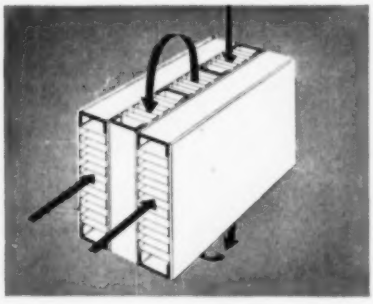
Many types of surface available. The brazed aluminum fins may be straight and continuous. Or they can be wavy, serrated or perforated to provide correct ratio of heat transfer to pressure drop.



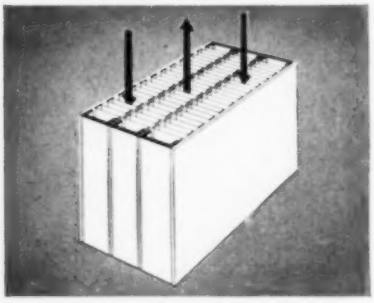
Exploded view shows component parts of a single passage. Fins, channels and parting sheets, all made from aluminum brazing sheet, become integrally bonded when assembled unit is submerged in a molten salt flux bath.



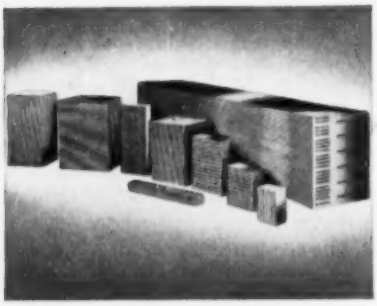
Cross-flow arrangement has fins in adjacent passages running crosswise to each other. TRANE Brazed Aluminum Surface can pack 450 square feet of heat transfer surface into one cubic foot of space.



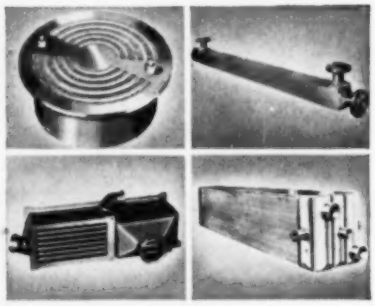
Multi-pass arrangement, like the cross-flow type, has fins in adjacent passages running crosswise to each other. With this arrangement, however, alternate passages are constructed to produce multiple passes.



Counter-flow arrangement has fins in adjacent passages running parallel to each other. A wide variety of different types of corrugated fin sheets can be used to handle different fluids in the same exchanger.



A wide range of core sizes is available up to 106 inches in length. Either bolt-on or integrally welded headers can be provided. Individual cores can be welded together to form larger multi-core units.



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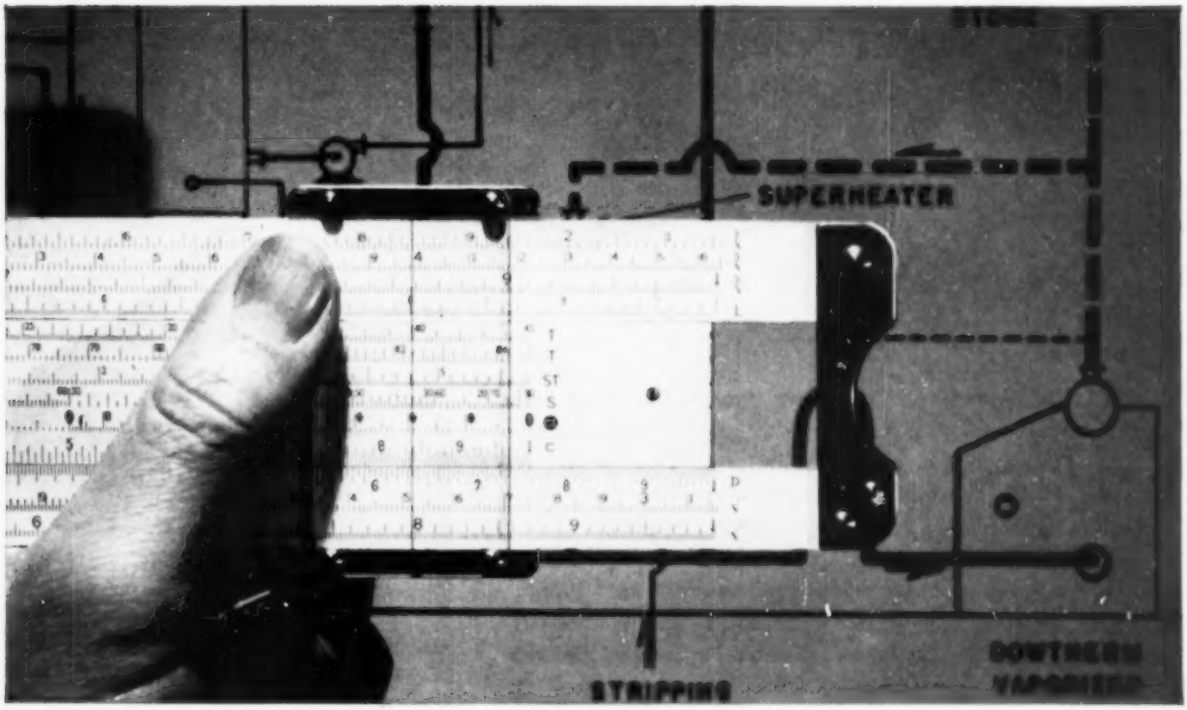

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Opinion and comment

THE STUDENT AND THE A.I.CH.E.

Most practicing chemical engineers are aware that the profession has been growing rapidly in numbers, particularly since World War II. Not so generally recognized is the fact that the present membership of A.I.Ch.E. is not much larger than the chemical engineering enrollment in colleges. In fact, in two years the colleges graduate about as many chemical engineers as the present number of Junior members in the Institute.

Various committees of the Institute have been working on the idea of arousing the interest of young graduates in A.I.Ch.E. so that the society truly represents the entire profession of chemical engineering. Until recently membership in the Institute developed largely as a result of initiative on the part of the prospective member. That this procedure has not been adequate is shown by the fact that only about one out of ten graduates has sought membership in the first year after graduation and less than twenty-five per cent have joined the society at any time during their careers.

Many years ago the Institute sponsored the growth of student chapters in departments of chemical engineering in various universities of the country. These have grown in number to approximately 100 chapters. In the institutions having student chapters about three quarters of all graduating seniors belong to such student groups. What needs to be done to encourage these men to continue their interest in the Institute after graduation?

It is probably fair to say that until rather recently the student chapters had not felt strong ties to the parent organization but rather had conducted their affairs as local campus groups. The recent introduction of Student membership in the national society, the growth of student regional meetings, and the introduction of methods for more ready transfer to Junior membership have all been of assistance in making the student cognizant of the activities of the Institute. Student-chapter counselors and other staff members are attempting also to do more to develop an understanding of the place of the Institute in the chemical engineering profession. Even so, the results, although encouraging, are certainly not yet satisfactory.

With the rapid growth of local sections of the Institute throughout the country in recent years, there is now available another potentially strong force to aid in developing the professional awareness of students. A number of local sections have taken several student chapters under their wing, and have shown a real interest in the activities of the younger men.

All local sections were asked recently to work with near-by student groups and to set up student-activity committees to act as a liaison between the local section and the student chapters. This assistance will be at its best, of course, when it is given freely and with real enthusiasm and not considered as a necessary evil. It will undoubtedly take on various forms, depending on the local situation, but certainly can include suggestions in the selection of speakers, guidance in the pros and cons of various fields of chemical engineering, aid in setting up good plant trips, and development of a feeling of comradeship and common interest.

Probably more than any other group of the Institute, local sections can influence prospective chemical engineers in their professional development. The future of the Institute depends on how thorough a job is done in showing these men not only that their professional society is of valuable assistance in their careers, but also that it demands responsibility and service on their part. This is a difficult task in these days of "what's in it for me?"

It is clear that the assistance given by the local sections to student chapters should be fitted to local needs. In some metropolitan areas, there is little difficulty in obtaining suitable speakers for chapter meetings, whereas in some localities it is difficult, even for the nearest local section, to help with the problem. It is also true that care must be taken not to try to direct the activities of the student chapters, but rather to offer assistance where it is needed. The relationship between the local section and the student group should therefore be fostered to achieve the best results.

There are several ways in which the local sections can assist with suitable speakers. One of these is to obtain the services of local-section members who are willing to speak on some phase of chemical engineering. In other cases when local-section members are visiting the location of the student chapter for business reasons, they can and should make arrangements to meet with the Student members. Sometimes it is possible to enlist the services of outside speakers who are to be in the locality either on business or to talk before other professional groups. Such procedures are just as effective and much to be preferred over any attempt to set up a national speakers' bureau for the student chapters.

Each local section will find its own way in which it can be of real assistance to the younger men. Methods which are workable in one locality will not necessarily be practical in other areas, and hence each section should use procedures adapted to the local needs.

It is hoped that the local sections will all take on this responsibility and aid in the development of a professional attitude in the young chemical engineers by working with them in the most impressionable years of their careers.

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Mixing—Present Theory and Practice

J. H. Rushton

J. Y. Oldshue

Illinois Institute of Technology, Chicago, Illinois

Mixing Equipment Company, Rochester, New York

J. Henry Rushton, the 1952 winner of the William H. Walker Award, is professor of chemical engineering, Illinois Institute of Technology, Chicago, Ill., and director of research, Mixing Equipment Co., Rochester, N. Y. Professor Rushton is a graduate of the University of Pennsylvania where he received both his B.S. and Ph.D. degrees. Before assuming his present position, he taught at the Drexel Institute, University of Michigan, and University of Virginia. During World War II he served as a technical aide and section chief with the Office of Scientific Research and Development. Dr. Rushton has been active in Institute affairs—he has served on many committees including the Education and Accrediting, Student Chapters, etc., and was elected a Director of the Institute in 1951 for a three-year term.

J. Y. Oldshue is head of development engineering for the Mixing Equipment Co. He has been engaged in fundamental and applied research in fluid mixing since going to Mixing Equipment Co. in 1950. He did graduate research in mixing at Illinois Institute of Technology prior to that time. Dr. Oldshue received his B.S. (1947), M.S. (1949), and his Ph.D. (1951) from Illinois Institute of Technology. During the war he was employed at the Los Alamos Scientific Laboratories, Los Alamos, N. M. At present he is serving as chairman of the Agitation Sub-Committee of the Equipment Testing Procedures Committee, A.I.Ch.E.

PART I

All chemical processing involves the mixing or interpenetration of one substance with another. Thus, the mixing of liquids with solids, gases, and other liquids is of major importance. This presentation deals only with the mixing of fluids of relatively low viscosity and does not cover the mixing of pastes or of solids with solids or gases. Many methods have been used to promote mixing, the most common of which is to move the fluid with a rotating impeller; the principal forms of impellers are the marine-type, various radial flow turbines, and simple flat paddles.

Although mixing is a commonplace operation, little concerted effort has been made until recently to understand its basic nature and how best to promote it for specific requirements. Historically, the operation of mixing usually was of minor importance from a cost standpoint, either for equipment or for operation. Mixing is accomplished often in a container in which another operation is taking place, and in the past these other operations usually were the most costly or critical ones. Attempts to measure mixing have for the most part been intimately connected with some particular process such as dissolving, oxidizing, or extracting; and no common criteria for mixing were evident. Furthermore, mixing will take place ultimately between various components by normal diffusion processes; hence, mixing is imposed only to hasten the desired interpenetration. Such forced interpenetration can be used also to control concentrations and concentration gradients, either of material or heat; accordingly, as chemical processing has become more demanding of control both for batch and continuous systems, more attention has been given to the operation of mixing. Further, the translation of laboratory bench-scale work to pilot plant to large-size production depends in large measure on reproducing the same environment with respect to mixing at the various stages. It is imperative, therefore, that mixing be understood of itself and not as specifically affecting one or another particular process.

The most fruitful approach to an understanding of mixing of fluids in all of its ramifications, has been by applying the ideas and principles of fluid mechanics. Mixing is mass transfer, and in fluids, mass transfer is a function of diffusion and fluid motion. The science of fluid mechanics is helpful and has numerous applications to the different problems of mixing.

Convection currents of molecular specie will be set in motion by natural diffusion, and in fact such motion may control a reaction rate. Forced convection may be imposed whenever the natural diffusion and convection rates are less than desired. Forced convection may result in either increased mass motion, or in turbulence, or in both; it is produced either by the application of mechanical energy (through a mixer) or by heat energy (as in a still pot). Thus, there are two principal actions of fluid motion which are inherent in a mixing operation: (1) the mass or macroscopic motion or translation of material over large distances, resulting in a major flow pattern, and (2) the small scale or microscopic motion commonly associated with turbulence and translation of material over small distances.

The large majority of all liquid mixing operations are carried out by rotating impellers. These impellers cause liquid to move, and in so doing effect mass flow and turbulence. The amount of flow and turbulence are functions also of the fluid properties and the physical position of all things touching the liquid. A knowledge of the interaction of each —impeller, fluid, container—is the basis of our present theories of mixing and of applications of machinery to bring it about.

Flow Pattern

For a brief review of the gross or mass motion of fluid resulting from the use of rotating mixing impellers in vertical axis, cylindrical tanks (the pre-

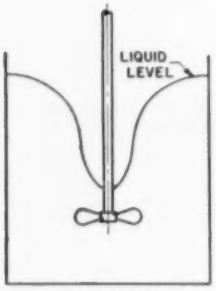


Fig. 1. Left, fluid flow pattern for any shape impeller when no baffles are used.

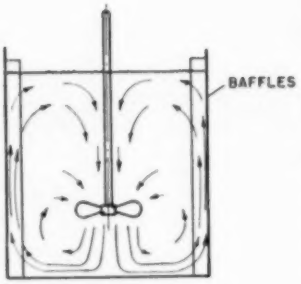
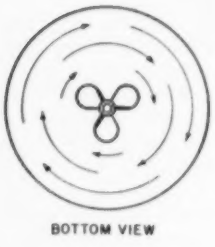


Fig. 2. Right, fluid flow pattern for propellers when baffles are used; axial flow pattern.



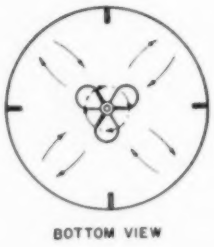
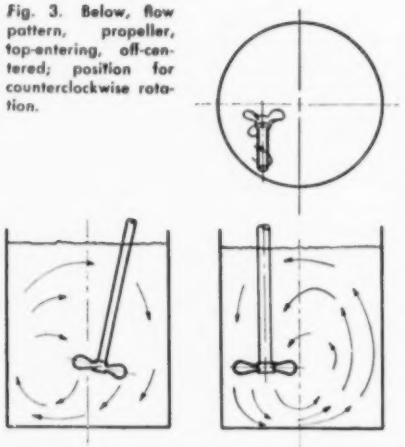


Fig. 3. Below, flow pattern, propeller, top-entering, off-centered; position for counterclockwise rotation.



ferred arrangement) see Figures 1-5. Many diagrams have appeared in the literature purporting to represent flow motion by various arrangements and impeller shapes. Those shown in Figures 1-5 are drawn on the basis of considerable photographic and visual evidence, and form the basis for classification of impellers (*24*). Furthermore, the power characteristics of impellers can correlate directly with the three principal flow patterns shown (*24*). The illustrations given here are typical of most mixing operations. There are many variations in the use of baffles, impellers, and tank fittings (*2, 24*).

Figure 1 illustrates the flow pattern for a single impeller of any shape—a marine propeller, a flat paddle, or a flat blade turbine (Fig. 6)—rotating in a low-viscosity liquid in a cylindrical tank without baffles. A vortex is formed around which the liquid swirls. The liquid moves in large circular paths, there is little motion from top to bottom, and in fact this motion often results in separation or stratification rather than mixing. Further, as impeller speed increases, more power must be applied to cause rotation, but the vortex becomes deeper at higher speeds until the vortex touches the impeller. When this happens, part of the impeller rotates in air or other gas, and power decreases. Thus, there is an upper limit to the ability to impose power for mixing under these conditions. For these reasons, an impeller is rarely used in the position shown, except for high-viscosity liquids (e.g., more than 20,000 centipoise) because they have sufficient internal resistance; they show little if any vortex motion; and the flow motion approaches that of Figures 2 and 5. If a propeller is placed too close to the bottom of a tank, the flow becomes radial like that shown in Figure 5.

The use of baffles can be avoided by certain "off-center" positions with propellers. Figure 3 shows a propeller shaft entering through the top surface of the liquid. When the propeller turns counterclockwise looking down the shaft, and the discharge is downward, the shaft is placed to the left of the center line and at an angle to vertical. The position is a critical one, depending on liquid depth and other size factors. Any significant change in location of the propeller will cause rotary flow similar to Figure 1. Portable propeller mixers and permanently mounted ones are frequently used in this way.

In large tanks propeller shafts can be mounted through the side of the tank. To avoid use of baffles to prevent swirl, the shaft is placed parallel to the bottom and to the left of a diameter when the rotation is clockwise. This gives a flow pattern as in Figure 4. This position is critical just as in Figure 3, but the rotation is opposite, although both are at an angle to the left of the center line. As yet there is no explanation for the fact that swirling can be eliminated by these off-centered positions and directions of rotation. The positions do result, however, in axial flow for a propeller. These positions also result in flow patterns equivalent to those obtained with baffles present.

A turbine (Fig. 6) or a flat paddle, when rotated in a tank without baffles, gives circular flow (Fig. 1), but when baffles are used the flow becomes radial. Hence, they are radial-flow impellers only when baffles or other obstructions are present, or when liquid viscosity is high. Figure 5 shows the flow pattern for the case when baffles are used at or near the side wall of the tank. This flow pattern is conducive to good mixing because it promotes lateral- and vertical-flow currents, and allows application of large amounts of power.

Figures 2-5, forming the basis for this discussion, are examples of flow patterns conducive to good mixing, and of best present practice. Many variations in tank shapes and fittings are used. Bottoms are often dished-out or conical, and heating and cooling coils or tubes are present. Discussions of the effects of such configurations are given elsewhere (*2*).

The mass-flow patterns just described are used to circulate liquid laterally and vertically throughout the vessel. Turbulence existing in the stream emerging from the impeller and generated during liquid flow is carried along in the primary or major mass-flow pattern. Both mass flow and turbulence are necessary for mixing, but some process applications require relatively more of one or the other. The mechanism of formation and propagation of turbulence in a mixing operation is the basis for modern theory and of sound mixing practice.

Mechanics of Moving Fluids

The following is a brief review of certain theories of modern fluid mechanics which have direct bearing on mixing. Detailed background and derivation of many of the relationships shown here can be found in (*17, 18*).

The behavior of moving fluids depends on density, viscosity, velocity, and distance. In this discussion, density will be considered as constant. Distances will be used as lengths in a three-coordinate system, with the conventional axes, x, y, and z. Distances are used also to show a length of travel, and as the basis for a gradient. Viscosity is that property of a fluid which gives rise to internal stress (shear stress τ) opposing deformation of a fluid mass. Velocities are vectorial and give the ratio of distance to time. Effects of viscosity and velocity are of major interest.

Velocities

A fluid mass flowing along a stream line at constant velocity has an average velocity equal to that of the instantaneous velocities at all points on the path. Such flow occurs only during viscous or laminar motion. A fluid mass may move

along a stream line with different instantaneous velocities at successive points along the line. Thus, if v signifies an instantaneous velocity, v' is used to indicate a velocity fluctuation, and $\bar{v}$ is used for the temporal mean velocity, these velocity vectors are related by

$$v = \bar{v} + v' \qquad (1)$$

Figure 7 is a plot of velocity measurements made of a turbulent flow as it passed a reference point moving in the direction x. The ordinate is the instantaneous velocity v and the abscissa is time. Illustrative values of $\bar{v}$ and v' are shown on the plot. Flow as indicated in Figure 7 is typical of turbulent flow.

Velocity fluctuations are both positive and negative in sign and direction and must average zero algebraically. However, the r.m.s. values ($\sqrt{\overline{v'^2}}$) can be used to eliminate the change in sign and give significance to the deviations of v' and $\bar{v}$. When a velocity fluctuation in a moving body of fluid occurs along an axis x, it is accompanied by a fluctuation along both the y and z axes. If the fluctuation is positive along one axis, it may be positive along another axis, but must be negative along the third axis. A complete picture of velocity fluctuations can be given in terms of the three planes x-y, y-z, and x-z. Experiments have confirmed the fact that v_x', v_y', and v_z' are related quantitatively in each of the three planes. Ratios of the form

$$\frac{(\overline{v_x' v_y'})}{(\sqrt{\overline{v_x'^2}} \times \sqrt{\overline{v_y'^2}})} \qquad (2)$$

for the x-y plane can be written for all three planes. Since v' is a characteristic of turbulence, it is clear that turbulence is not random but is dependent upon v' in all three planes and that they are interrelated.

Viscosity and Shear Stress

Dynamic viscosity is defined as the ratio of stress to the rate of fluid deformation. For the x-y plane,

$$\mu = \frac{\tau}{dv/dy}$$

and shear stress τ due to viscosity is:

$$\tau = \mu \frac{dv}{dy} \qquad (3)$$

The deformation shown here is in terms of change of instantaneous velocity with distance at right angle to the velocity, dv/dy. Actually, the deformations which occur in a small fluid mass over which there is a velocity gradient are of two types; linear deformations, and angular deformations; that is, the sides of the mass elongate or shorten with all sides remaining parallel, or, the sides may move so that the angles between the sides become different. In addition to these deformations, it should be noted that the fluid mass may also move in simple translation from one point to another without deformation, or it may rotate around one point in its body due to the couple effect of the forces at the sides of the mass.

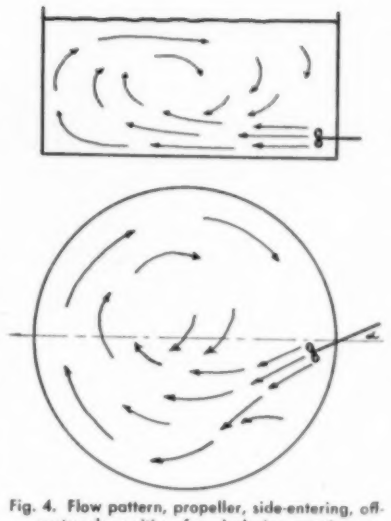
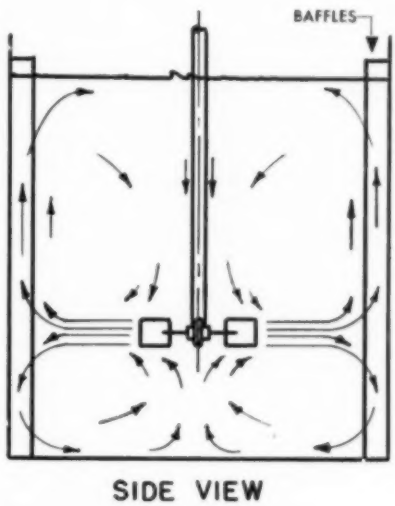


Fig. 4. Flow pattern, propeller, side-entering, off-centered; position for clockwise rotation.



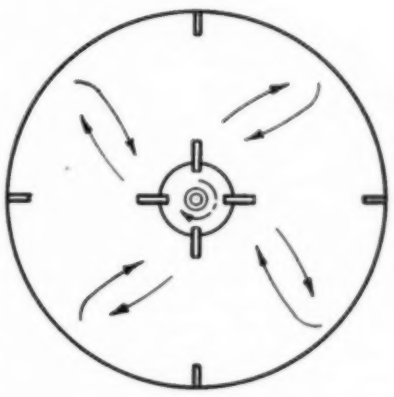


Fig. 5. Flow pattern for turbines with baffles; radial flow pattern.

Equation (3) may also be written in terms of averages or of fluctuations by using $\bar{\tau}$ and $\bar{v}$, or τ' and v'. The dynamic viscosity μ is known to depend on density, velocity, and mean free path of molecules, but is independent of the state of motion of the fluid (laminar or turbulent).

Laminar Motion and Turbulence

Figure 7 is a typical trace of turbulent flow of liquid flowing past a point in space. The dashed line corresponding to $\bar{v}_x$ could be thought of also as a plot of instantaneous velocity for viscous or laminar flow. A basic question in fluid mechanics concerns the stability of laminar motion and under what conditions a flow will become unstable. Recent quantitative measurements of turbulence confirm the basic theory that viscosity, velocity, and frequency of velocity fluctuations are interrelated. A disturbance of whatever cause, that results in a velocity fluctuation v' must cause an acceleration of fluid from one instantaneous velocity to the next, since $v' = v - \bar{v}$. Hence, the Reynolds number has significance as a ratio of accelerative force to viscous force. The Reynolds number therefore can be used as a criterion of flow stability, and implies that there is a relation between shear stress and viscosity which will show the limit of velocity gradient (in Equation (3)) above which velocity fluctuations will not only occur but also will persist. It has been repeatedly demonstrated that for a given viscosity fluid moving in steady laminar flow, as the velocity gradient is increased a value of dv/dy will be reached at which fluid deformation will take place and velocity fluctuations will occur. These fluctuations result in the formation of eddies and in transfer of mass and momentum in directions perpendicular to the principal flow. Such flow is turbulent. If disturbances are imposed and the resulting velocity fluctuations do not maintain velocity gradients sufficient to overcome viscosity, the disturbances will be damped out and the fluctuations will disappear. Therefore, regardless of how turbulence may be formed, it will persist only if the deformations, or gradients, are sufficiently intense to overcome the stabilizing effect of viscosity.

When flow is turbulent it is helpful to differentiate between the velocities involved in the basic flow pattern of translation, and the secondary movement

within the basic flow. The instantaneous velocity vector at a point is the vector sum of $\bar{v}$ and v', $\bar{v}$ referring to the basic flow and v' to the secondary flow. v' may be thought of as the instantaneous velocity of the eddy, and $\bar{v}$ as the velocity with which the eddy moves past the point of observation.

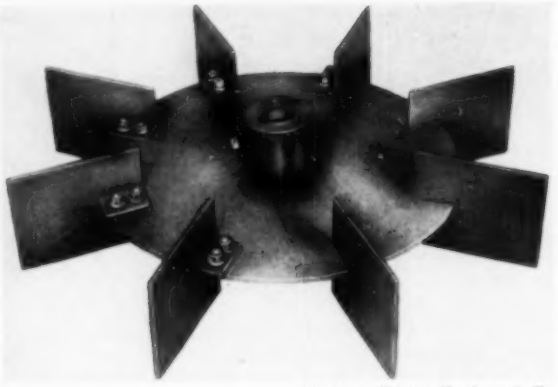


Fig. 6. Flat blade turbine.

Courtesy, Mixing Equipment Co.

Momentum Transport

In turbulent motion fluid masses are carried back and forth across flow planes whenever velocity fluctuations exist. When the transported mass adapts itself to the velocity conditions of its new surroundings the change in momentum will equal the product of the fluid density and the velocity of fluctuations, v'. The force per unit area over which the momentum transfer takes place is equal to the stress caused by the momentum transport. Mass is transferred in any momentum transfer, and this basic movement of mass is the primary process of mixing; it is brought about by the secondary flow motion.

Consider a small mass of fluid flowing in the x-y plane across a line parallel to the x-z plane. The velocity fluctuation v_y' exerts a normal force in the y direction; also a tangential force in the x direction is due to v_x'. A pressure fluctuation p_y' will exist in the y direction, and a stress fluctuation τ'_{xy} will exist in the x-y plane. These forces and stresses can be formulated as

$$p_y' = \rho v_y'^2 \qquad (4)$$

$$\tau'_{yx} = -\rho v_x' v_y' \qquad (5)$$

They may be written in terms of average values, and also in terms of any of the coordinate positions. It is evident that velocity fluctuations in one plane produce mass transport into other regions, and that this is accompanied by pressure fluctuations.

Turbulence

Boussinesq, in 1877, related the total shear stress occurring in turbulent flow to molecular motion, viscosity, and velocity gradient by assuming that a "molar" or eddy viscosity, η, could be used in a corresponding way. The concept has proven to be useful and is formulated from Equation (3) as

$$\bar{\tau} = (\mu + \eta)\frac{d\bar{v}}{dy} \qquad (6)$$

The molecular viscosity μ is constant at all points in a homogeneous fluid, but η will vary depending on the turbulence. Equation (6) may be expanded to

$$\bar{\tau} = \mu\frac{d\bar{v}}{dy} + \eta\frac{d\bar{v}}{dy} \qquad (7)$$

Also, the average stress in turbulent flow must equal the sum of the average stresses due to viscosity, and to momentum transport or velocity fluctuations. The stress due to momentum transport is given in Equation (5). Therefore, by combining Equations (3) and (5), the stress in turbulent flow is:

$$\bar{\tau}_{turb.} = \mu\frac{d\bar{v}}{dy} - \rho\overline{v_x' v_y'} \qquad (8)$$

From Equations (7) and (8)

$$\eta\frac{d\bar{v}}{dy} = -\rho\overline{v_x' v_y'}$$

and

$$\frac{\eta}{\rho} = \epsilon = -\frac{\overline{v_x' v_y'}}{d\bar{v}/dy} \qquad (9)$$

where η/ρ is the kinematic eddy viscosity ϵ. This ratio is a direct measure of the transport capacity of the mixing process by way of momentum transfer. Eddy viscosity is therefore a useful index for mixing, as will be shown later.

The dimensions of ϵ are L^2/T, or Lv, and ϵ has the same units as kinematic viscosity. The ratio of kinematic eddy viscosity to kinematic viscosity, ϵ/ν, is the Reynolds number Lv/ν.

The Reynolds number is given significance in numerous ways, via.: the ratio of accelerative, or dynamic, or inertial, or turbulent forces to viscous forces. The concept of eddy viscosity is simply a "turbulent viscosity," the ratio of a shear stress to a velocity gradient. A shear stress may be caused either by dynamic viscosity (which is a molecular property) or by turbulence. Both can, therefore, be expressed in terms of a velocity gradient (Equations (3) and (7), respectively) of fluid motion.

Further insight to the mixing process due to eddy current turbulence was proposed by Prandtl, who postulated a mixing length l to be similar to the mean free path of molecular motion. He postulated a mixing length as that distance which a small fluid mass would travel before it would give up its momentum to the region to which it moved. Prandtl's simple concept is useful qualitatively, but does not take into account the change in l with velocity gradient and position. Developments stemming from this concept have led to more rigorous relations by which eddy size can be related to turbulence. On the assumptions that the lateral flow produced by an eddy is effective over the distance l in the y direction, that v_x' and v_y' are proportional, the following velocity proportions can be written

$$\overline{v_x'}l \propto \overline{v_y'}l \propto l^2\frac{d\bar{v}}{dy}$$

but

$$\overline{v_x'}l \propto \frac{\overline{v_x' v_y'}}{d\bar{v}/dy}$$

and then

$$\epsilon = -\frac{\overline{v_x' v_y'}}{d\bar{v}/dy} \propto v_y'l \propto l^2\frac{d\bar{v}}{dy}$$

Experimental data indicate that the assumptions are essentially correct and, therefore, the kinematic viscosity may be related most conveniently to an average velocity fluctuation and the average size l of the eddies by

$$\epsilon = \beta l\sqrt{\overline{v_y'^2}} \qquad (10)$$

The proportionality constant β is a function of the fluid and boundary conditions.

Since ϵ is proportional to Ll in a turbulent fluid, and is a measure of turbulence, it is clear that a given value of ϵ may be the product of a large or small value of eddy size, or scale, and a small or large eddy velocity, respectively. Moreover, in a flowing system where turbulence is spreading, the scale and velocity of eddies is continually changing; accordingly the values of eddy size and velocities in Equation (10) are over-all averages.

Some years ago a jingle appeared in the fluid mechanics literature which expresses the interrelation between eddies

and viscosity better than most word pictures. It is:

> Big size whirls have little whirls
> That feed on their velocity.
> Little whirls have lesser whirls
> And so on to viscosity.

Entrainment

Since mass and material are transported in all directions by the mixing process of turbulence, it follows that turbulence will spread in all directions in a flowing stream. Not only will rapid-moving liquid masses be moving into slower moving zones, but also slow-moving liquid will be entrained into more rapid zones. The phenomenon of entrainment is well illustrated by the flow of a submerged fluid jet.

Figure 8 is a schematic diagram of the spread of a circular jet in the x-y plane. The jet is here flowing into a quiet fluid. Near the boundary of the jet where high velocity flow is adjacent to low velocity flow (a velocity discontinuity) the dv/dy is sufficient to create instability and to initiate turbulence. After this, the turbulence spreads toward the center of the stream and also into the quiet fluid. By momentum transfer, material is accelerated at the boundary of the flow (where dv/dy is sufficiently high) and becomes a part of the flowing jet. Velocity profiles across the jet will vary with distance from the jet entrance, and at some distance the velocities will decrease to such a value that there will no longer be a sufficiently large value of dv/dy to cause more entrainment. During this entire process, mixing will be proceeding between the surrounding fluid and the jet, and within the jet. Indeed, the entrainment of fluid by this process can be used as an index of mixing.

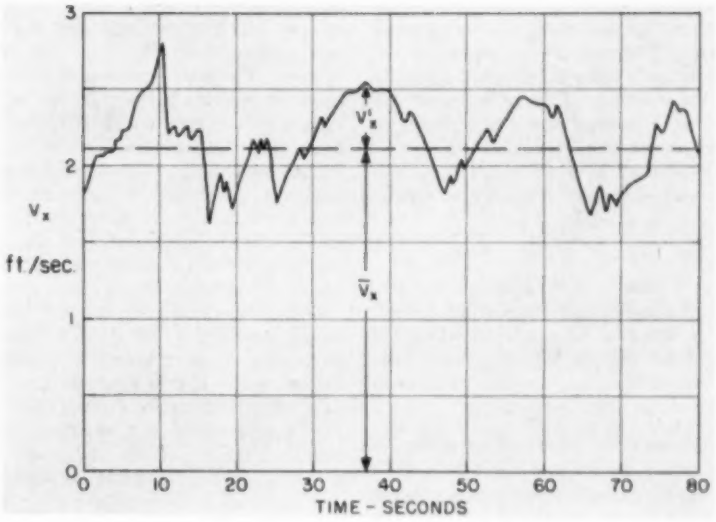


Fig. 7. Velocity fluctuations in turbulent flow.

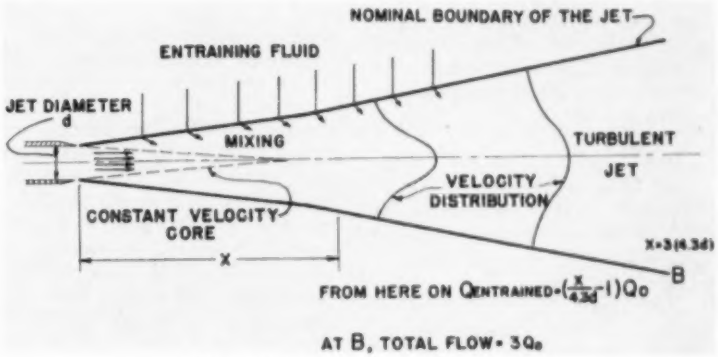


Fig. 8. Flow of a submerged circular jet.

The spread of a steady-flow turbulent jet of circular cross section has been found to spread at an angle whose slope is about 1 to 5. Jets of water flowing into water entrain surrounding water approximately as

$$Q_e = \left[0.23\left(\frac{X}{D_o}\right) - 1 \right] Q \qquad (11)$$

If, for example, a jet entrains liquid for 40 diameters, the amount of water entrained and mixed with the jet would be 8.2 Q, where Q is the rate of flow at the entrance, X is the distance along jet axis, and D_o is the entrance jet diameter. Jets may entrain for distances up to 80 diameters, depending on the velocity of the jet.

Diffusion and Mass Transfer

An interchange of fluid between two adjacent zones which results in mixing involves the simultaneous interchange of all local characteristics of the fluid and flow. The rate at which velocities or other properties of adjacent zones will change, depends on the convection capacity of the cross flow and the difference in characteristics between the two zones. The same rates of transfer could result from a low-velocity cross-flow carrying over a large lateral distance, or from a high-velocity cross flow carrying over a small distance. This follows from the nature of turbulence, and from the evidence that turbulence is the product of eddy size and velocity. Thus a forced-convection diffusion, or mass-transfer coefficient, will represent a combination of length and velocity which together characterize the mixing process. Mass transfer is a combination of molecular diffusion and turbulent or forced convection mixing. If the principal flow is laminar the transfer coefficient is proportional to the kinematic viscosity of the fluid, and if the flow is highly turbulent the transfer coefficient becomes proportional to the kinematic eddy viscosity. The rate of turbulent diffusion, or transfer, will usually be large compared to molecular diffusion.

For the characteristic of momentum, the mass-transfer equation involving shear for laminar flow is

$$\tau_{lam} = \nu \frac{d(\rho \bar{v})}{dy}$$

and for turbulent flow

$$\tau_{turb} = \epsilon \frac{d(\rho \bar{v})}{dy}$$

In terms of mass transfer for turbulent flow

$$M_{turb} = -\beta \epsilon \frac{dc}{dy}$$

where M is the rate of transport, and dc/dy is the concentration gradient.

Dissipation of Energy During Flow

A continuous deformation of a moving fluid is opposed by viscous stresses, and the motion can only continue if energy is supplied to overcome the viscous resistance. Such a process, therefore, involves the continuous transformation of mechanical energy into heat. It has also been shown that kinetic energy of flow can be converted to heat only through viscous shear developed in linear and angular deformations.

In turbulent flow, the viscous stresses

within the eddies are the means by which mechanical energy is transformed to heat. The rate of dissipation of energy depends upon the dynamic viscosity and the intensity of turbulent eddy motion. It follows that the dissipation of turbulence is through viscous action.

The energy in a flowing stream can be expressed as rate of energy, or power, and may be formulated as

$$P = QH \tag{12}$$

where P may be in foot pounds per second, Q, the flow, in pounds per second, and H, the total head against which the mass flows, in feet. For one pound flowing per second, the equation reduces to one of heads alone, and

$$H = H_{kinetic} + H_{pressure} + H_{potential} \tag{13}$$

The kinetic head is often called a velocity head, but if the average velocity of flow is used to calculate the kinetic head, as $\bar{v}^2/2g$, it will represent the kinetic energy of flow in the x direction only, and will not take into account the kinetic energy of turbulence in the secondary flow. Thus, $H_{kinetic}$ must include that due to the average velocity and that due to the eddy velocity, or

$$H_{kinetic} = \frac{\overline{v^2}}{2g} + \frac{\overline{v'^2}}{2g} \tag{14}$$

In cases where fluid is not elevated (as in most mixing operations), $H_{potential} = 0$. Equation (13) can be written:

$$H = \frac{\overline{v^2}}{2g} + \frac{\overline{v'^2}}{2g} + \frac{p}{\gamma} \tag{15}$$

The kinetic energy head of the mean flow can be determined readily from measurement of flow Q since $\bar{v} = Q/\gamma A$ where γ is specific weight and A is the area through which flow takes place. But it is difficult to determine the value of the kinetic energy of the turbulence, because eddy flow cannot be measured and $\bar{v}'$ is difficult to determine. If the pressure head can be measured, then the value of $\overline{v'^2}/2g$ can be approximated by the difference in Equation (15).

Energy in turbulent flow can be dissipated only by viscous shear (and wall friction) within the eddies. Therefore, if eddy turbulence is maintained, it must be at the expense of the kinetic energy of the main flow and by the pressure gradient. The energy of turbulence can never be restored to the kinetic energy of the principal flow.

Similarity Concepts

A useful tool in fluid mechanics analysis is that of similitude, and it is of considerable significance in mixing. There are three types of similitude; geometric, kinematic, and dynamic. Geometric similarity refers to linear dimensions, and two systems are said to be geometrically similar when the ratios of corresponding dimensions in one system are equal to those of the other system. Kinematics refers to motions, and two systems are similar in motion when they are geometrically similar and have the same ratio of velocity vectors for corresponding points in each system. Dynamic similarity is achieved when two systems are geometrically similar and kinematically similar, and also have all force ratios equal for corresponding points in the two systems.

Use of the similarity concept has allowed correlation of fluid properties, motions, sizes, and forces to be related systematically in mixing operations (*19, 24*). Furthermore, it forms the basis for relating action in a small system to that in a larger system, and orients laboratory and pilot plant experiments with scale-up problems (*20*).

Mechanics of Flow in Mixing Tanks

Flow motion in a mixing tank as illustrated in Figures 2-5 is produced by rotating impellers running openly without casings, and the feed and discharge streams are free to move without close-fitting solid-guide surfaces. The final principal and secondary motions are dependent primarily on the impeller shape, speed, and location; on the fluid density and viscosity; and on the physical configuration of the tank and its fittings. It is usually desirable to provide conditions such that the principal flow pattern provides lateral- and vertical-flow currents extending to all portions of the container; one of the types in Figures 2-5. Sometimes process requirements are such that modifications of these flow patterns are desired. Such a case might arise in mixing light solids which are difficult to wet. By allowing the surface to swirl and vortex slightly, a funnel can be simulated, down which the solids will be directed to the impeller. Such a vortex can be provided by placing the top of the baffles below the liquid surface. In fact, whenever the effect of swirl or a centrifugal separating effect provided by rotary motion is desired, modification of the extremes of flow pattern such as Figures 1 and 2 (or by changing the amount of off-centering in Figs. 3 and 4) can be made. In general, however, these modifications are exceptional and do not constitute the large majority of mixing-equipment arrangements. Occasionally, draft tubes are used to confine and direct the feed to the inlet of impellers, but their use is not often necessary. The feed to open-running impellers is from any direction involving the minimum resistance to flow, whereas the discharge flow is well directed and guide tubes are rarely used to direct discharge flow.

Because of the free-feeding nature of mixing impellers and the unhampered discharge streams, the mechanics of the secondary motion of turbulence and the energy necessary to produce both the primary and secondary motions are of prime importance in mixing. To bring about mixing, work must be done to produce the two flow motions; the power required to provide such flows has been evaluated for the types of primary motion shown in Figures 1-5 for a wide variety of impellers, fluids, and tank conditions. Some data are available for the quantity and velocity of flow from mixing impellers and there is some information on the amount of turbulence and where it is formed (*27, 29*).

Power Characteristics of Mixing Impellers

Comprehensive data on the interrelation of impeller speed and diameter, fluid density and viscosity, and physical configuration of the tank and fittings, and the power necessary to move the impeller have been published (*24*), and basic theory pertaining to the correlations is covered in the literature cited. Figure 9 is illustrative of the correlation between Reynolds number and power number. The Reynolds number for mixing is based on impeller diameter D, speed of rotation, N, and on the viscosity and density of the liquid; it is formulated as $(D^2N\rho/\mu)$. The power number is based on the same properties, and is formulated as $(Pg_c/\rho N^3D)$. A logarithmic plot of the power number, N_P, and the Reynolds number N_{Re} give curves like that of line $ABCD$ when there is no swirl or vortex in the liquid, and curves like line ABE when vortex exists. Actually, line ABE can be general only when the Froude number (DN^2/g) is used (*19, 24*).

The line AB of Figure 9 is indicative of viscous-type flow, and exists at low Reynolds numbers where viscous forces dominate flow. As Reynolds number increases, a transition region appears as shown between points B and C, and between C and D the turbulent forces predominate in the flow. The region between C and D is that wherein the turbulence is fully developed. From such correlations the following general equations were derived:

For conditions of viscous flow, curve AB,

$$P = \frac{K}{g_c}\mu N^2D^3 \tag{16}$$

and for fully developed turbulent flow,

$$P = \frac{K}{g_c}\rho N^3D^5 \tag{17}$$

Equations are not given here for the transition range or for conditions like curve BE, because the slopes are not constant and the equations have little practical value.

The constants K of Equations (16)

and (17) are different. Also, the constants are dependent on the impeller shape and all physical boundary conditions. Values of K are given in Table 1 for both equations for a variety of impellers (*24*). The impellers are for rotation on the center line of a vertical cylindrical tank, flat bottom, liquid depth equal to tank diameter, impeller diameter one third of the tank diameter, and the impeller one diameter above tank bottom, and four baffles each one tenth of the tank diameter at the side wall.

Off-centered propellers as shown in Figures 3 and 4 have the same values of K as when the four standard baffles are used. The correlations cover a wide range of sizes and the constants can be used for dimensionally similar systems of all sizes encountered in industrial mixing operations. For example, data for the value of K for fully developed turbulence for the standard flat blade turbines of Mixing Equipment Co., were determined from turbines from 4-in. to 48-in. diam., and have been verified for larger sizes.

Values of K will vary with boundary and other shape changes. Values of K for other impeller positions and variables are also available (*11, 24*).

Power alone is not an index to mixing, however, the efficiency or cost of mixing must ultimately be compared on the basis of power or energy expended. Hence, a comparison of mixer performance must be made on the basis of power. Therefore, it is important to know the interrelations between power, size, and impeller speed, and the quantities and velocities and turbulence in mixing streams.

For fully developed turbulent flow, Equation (17) states that for a given fluid the power is proportional to the cube of the speed of impeller rotation and the fifth power of diameter. Therefore, at constant power

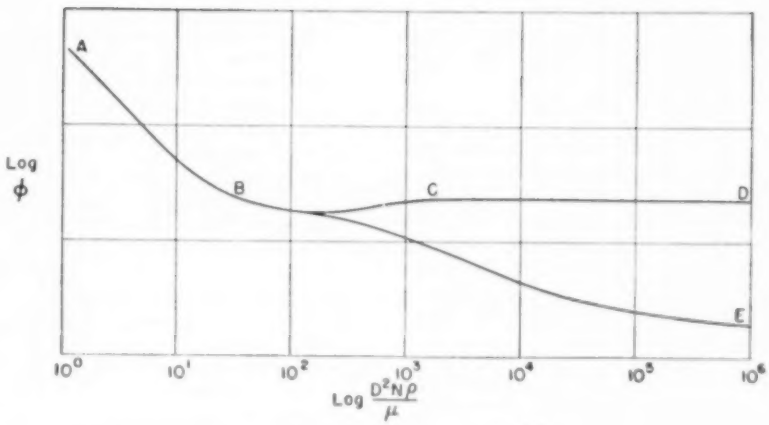
$$N_r = D_r^{-5/3} \qquad (18)$$

$$D_r = N_r^{-3/5} \qquad (19)$$

where the subscript r refers to the ratio at conditions 2 to 1.

For example, for constant power an impeller of twice the diameter must rotate at a speed of N_2, such that the speed ratio N_2/N_1 from Equation (18) will be $(\frac{1}{2})^{1.67}$ or 0.315. In other words, the new speed will be 31.5% of the speed of the smaller impeller. This is strictly correct only for geometrically similar systems. However, the ratio of impeller to tank diameter D/T has little effect on power over rather wide ranges of D/T (*24*), hence, Equations (18) and (19) are approximately correct when the size of impeller is changed in a constant-diameter tank.

Equation (12) states the relation between power, flow, and total head. In



FOR CURVE-ABCD-NO VORTEX PRESENT $\phi = \frac{Pg}{\rho N^3 D^5}$

FOR CURVE-BE- VORTEX PRESENT $\phi = (\frac{Pg}{\rho N^3 D^5})(\frac{DN^2}{g})^{-n}$

Fig. 9. Typical power characteristics of a mixing impeller.

TABLE 1.–DATA FOR POWER CONSUMPTION OF MIXING IMPELLERS (*24*).

	Values of K	
	Eq. (16) Viscous	Eq. (17) Turbulent
Propeller 3-blade, pitch = diameter	41.0	0.32
Propeller 3-blade, pitch = 2 diameters	43.5	1.00
Turbine, flat blade (Fig. 6), 4 blades	71.0	6.30
Turbine, flat blade 6 blades	71.0	6.30
Turbine, flat blade 8 blades		
Fan Turbine, blades at 45°, 6 blades	70.0	1.65
Shrouded Turbine, Stator ring[1]	172.5	1.12
Flat paddles, 2 blades (single paddle), $D/W = 4$*	43.0	2.25
Flat paddles, 2 blades $D/W = 6$*	36.5	1.60
Flat paddles, 2 blades $D/W = 8$*	33.0	1.15
Flat paddles, 4 blades, $D/W = 6$*	49.0	2.75
Flat paddles, 6 blades, $D/W = 6$*	71.0	3.82

In cylindrical tank, four baffles each 1/10 tank diam.; impeller 1/3 tank diam.; impeller 1 diam. above flat bottom, liquid depth equal to tank diameter, impeller shaft vertical and at centerline of tank. Data for flat paddles, marked by asterisk, are calculated from Mack (*14*).

[1] Effect of change of variables (*24*).

TABLE 2.–TYPICAL RELATIONS BETWEEN IMPELLER AND FLOW VARIABLES

Example: Table shows that at constant power $H_r = N_r^{4/5}$, or $= D_r^{-4/3}$
At constant diameter, $P_r = N_r^3$

At Constant	P_r	D_r	N_r	Q_r	H_r	$(Q/H)_r$
P	.....	$N_r^{-3/5}$	.....	$N_r^{1/5}$	$N_r^{4/5}$	$N_r^{-3/5}$
	.....	.....	$D_r^{-5/3}$	$D_r^{-4/3}$	$D_r^{-4/3}$	$D_r^{5/3}$
D	N_r^3	.....	$P_r^{1/3}$	N_r	N_r^2	N_r^{-1}
N	D_r^5	$P_r^{1/3}$	.....	D_r^3	D_r^2	D_r

the following section it will be shown that flow from mixing impellers is proportional to speed of rotation and to the cube of size, thus,

$$Q \propto ND^3 \qquad (20)$$

For a given impeller it is evident that an increase of speed to twice the original will result in twice the flow but will require two cubed, or eight, times the power input. Thus, the power increases more rapidly than flow. For the comparisons at constant power, however, substitution of Equation (20) in Equation (17) gives

$$P \propto QN^2D^2$$

so that H in Equation (12) must be proportional to N^2D^2, or

$$H \propto N^2D^2 \qquad (21)$$

For flow at constant power input, substitution of Equations (21) and (19) in (12) gives

$$Q_r = N_r^{-4/5} \qquad (22)$$

similarly, with Equation (20)

$$H_r = N_r^{4/5} \qquad (23)$$

Flow can be related also to speed and diameter by use of Equations (18), (20), and (21) in the same way. A few of the more useful of many relations of this sort are tabulated in Table 2.

The significance of Equations (22) and (23) are best shown by an illustration. For constant power input, if speed is doubled, how will flow and head vary? Substitution in Equation (22) shows that $Q_2/Q_1 = (\frac{1}{2})^{0.8}$, or 1/1.74, or 0.575. Thus, the flow is reduced to 57.5% of the original flow and head (from Equation (23)) is increased 1.74 times or 174%. Since head is proportional to turbulence, it is clear that in this case, for the same power input the smaller impeller running at higher speeds in the same diameter tank or a dimensionally similar tank, will give less flow and more turbulence than the larger impeller. As will be shown later, some process reactions are dominated by flow, while others are sensitive to head and turbulence. This analysis shows that for constant-energy input, the flow and head ratio can be varied by size and speed effects alone for a given impeller design, provided that characteristics of impellers as indicated by Equation (17) and (20) are known. It is essential, therefore, that pilot-plant work be conducted with calibrated impellers so that the power characteristics are known, and then the effect of the independent variables of turbulence and flow can be related to process results, at the same rates of energy input.

Notation

Any consistent set of units may be used; some are given here for illustration in foot, pound, second, degrees Fahrenheit, and mole units.

A = area
c = heat capacity of liquid; also, concentration
d = diameter of tube, for dimension parameter in Nusselt number
D = impeller diameter, ft.
D_d = diffusivity
D_o = jet diameter at origin
g = gravity constant
g_c = gravity conversion factor
h = film coefficient of heat transfer
H = head, ft.
k = thermal conductivity of liquid
k_l = liquid film mass-transfer coefficient
K = a constant
l = mixing length, eddy scale, ft.
L = a length, ft.
N = impeller speed, rev./sec.
N_P = power number
N_{Re} = Reynolds number
p = pressure; also, exponent of Prandtl group
P = power, ft. lb./sec.
Q = flow rate, lb./sec. or cu.ft./sec.
Q_e = entrained flow rate
s = exponent of Schmidt group
T = tank diameter, also time
v = velocity, instantaneous, vectorial, ft./sec.
$\bar{v}$ = velocity, average, vectorial
v' = velocity fluctuation, $v' = v - \bar{v}$
V = volume
W = width of impeller blade
x = slope of correlating line, mixing slope
X = distance from jet origin

$\propto$ = proportional to
γ = specific weight, lb. force/cu.ft.
ϵ = kinematic eddy viscosity, η/ρ
η = eddy viscosity
μ = dynamic viscosity
μ_f = dynamic viscosity at mean film temperature
μ_s = dynamic viscosity at temperature of solid surface
ν = kinematic viscosity, μ/ρ, sq.ft./sec.
ϕ = a function, a group of dimensionless units
ρ = density, lb. mass/cu.ft.
τ = shear stress, lb. force/sq.ft.
ψ = a function, a group of dimensionless units

Subscript 1 refers to condition 1
Subscript 2 refers to condition 2
Subscript r indicates ratio
Subscript x, y, z refer to directions in the x, y, z axes respectively
Superscript bar indicates average
prime indicates fluctuation condition

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Part II will be run in an early issue.

Atomization by Centrifugal Pressure Nozzles

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A study was made of centrifugal pressure nozzle atomizers to develop quantitative performance data on spray distribution, drop-size distribution, and capacity for a range of pressures, orifice diameters, and spray cone angles. Mean drop size, drop-size uniformity, and cone angle were correlated empirically with the liquid tangential and vertical velocities, and the orifice diameter. Results showed the importance of a tangential velocity component in producing atomization and appreciable cone angles.

A comparison of the drop-size distributions for sharp-edged and round-edged orifices was made. Irregularities in orifice shape were found to have a marked adverse effect on uniformity of spray pattern. An increase in the number of inlet passages in a whirl-chamber-type nozzle improved spatial uniformity but decreased cone angle. A maximum cone angle was achieved when these inlets were tangential with respect to the whirl-chamber wall.

A preliminary study of the effect of viscosity showed that an increase in liquid viscosity for a given nozzle at constant capacity increased the mean drop size until a viscosity was reached at which atomization no longer occurred.

Part I

Processes involving the atomization of liquids play a significant role in chemical industry. Spray drying, spray cooling, and spray absorption are a few notable examples. In most spray operations, equipment performance is influenced to a large degree by the spray characteristics of the atomizer. To date only fragmentary information is available concerning the relationships between these characteristics and the variables associated with atomizer design and operation. The characteristics of an atomizer of usual interest are: (1) drop-size distribution, (2) spray distribution, (3) atomizer capacity, and (4) power requirements.

The more common devices for dispersing liquids into a finely divided state include pneumatic or two-fluid atomizers, spinning disks, impact-type nozzles, and jet and centrifugal pressure nozzles.

This study was made to correlate the spray characteristics of centrifugal pressure nozzles with their principal design and operating variables. A few tests were made to observe the effect of liquid viscosity upon drop-size distribution. No other liquid properties were studied. Attention was given to methods of determining and representing drop size and drop-size distribution. Such data are important in determining the time of drying and product characteristics in spray dryers, the effectiveness of combustion in engines and burners, and the rates of reaction and absorption in spray towers.

The principal factors of nozzle design which influence the spray characteristics are: (1) the orifice size which influences nozzle capacity and the film thickness of the liquid, and (2) the internal construction of the nozzle which influences the magnitudes of the velocity components and hence the degree of atomization. Thus, the principal factors of concern in this study were the structural features of the nozzle which affected the vertical and tangential velocity components of the liquid.

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Previous Work and General Considerations

The atomizing ability of centrifugal pressure nozzles is determined by internal design features. Cone-shaped sprays are obtained only if the liquid is given a tangential or vortical motion within the nozzle. When spiral grooves are used to do this, the tangential component and hence spray cone angle, will be increased by a reduction in groove pitch or by a reduction in groove cross-sectional area. In a so-called whirl-chamber-type nozzle, the liquid is given a spinning motion by flowing through inlets set at an angle to the chamber. Harvey and Hermandorfer (*9*), in a mathematical analysis of the flow of liquid in these nozzles, concluded that the tangent of half the spray cone angle was approximated by the ratio of the tangential velocity to the vertical velocity (measured at the orifice).

Doble (*6, 7*) developed empirical formulae relating capacity and cone angle to the internal dimensions of specific centrifugal nozzles, and he reported that cone angle increased with orifice diameter. From meager drop-size data, he concluded that drop diameter decreased with increasing d_o. This contradicts the results of this investigation and other investigators. Doble further observed that for some nozzles, the smaller droplets were thrown toward the outside of the spray pattern, while for certain others, the small droplets fell directly beneath the nozzle.

In addition to nozzle design, spray characteristics are a function of operat-

ing pressures. Capacity can usually be assumed to be directly proportional to the square root of the pressure, although Doble observed that the ratio $C/\sqrt{p}$ decreased slightly with pressure, where C is nozzle capacity and p is pressure.

Harvey and Hermandorfer (*9*) in a study of the effect of pressure on cone angle proposed that liquid in the whirl chamber may follow the action of either a free or a forced vortex. A free vortex usually predominates near the outside of the chamber, but as a given element of liquid nears the orifice, its tangential velocity becomes so high that frictional forces become appreciable, a forced vortex with constant angular velocity is formed, and the tangential velocity diminishes until the liquid is discharged. As the pressure is increased, the resulting higher velocities in the region of the free vortex will give rise to the forced vortex earlier. Consequently, the exit tangential velocity is smaller than before, resulting in a narrower cone.

By virtue of the greater energy involved at higher pressures, drop size ordinarily will diminish with increased pressure, although there are varying opinions as to the exact relation involved.

With regard to liquid properties, Kuehn (*12*), in tests with jet injectors, found that at high liquid velocities, corresponding to high pressures for pressure nozzles, droplet size was controlled by surface tension and inertial forces, whereas at low liquid velocities, viscosity was found to be the controlling liquid property. Schuebel (*29*) postulated a dimensional relation in which drop size varied inversely with viscosity. However, David (*5*) and Houghton (*11*) contended that an increase in viscosity results in a larger drop size. Glendenning et al. (*8*) observed that flow rates through plain orifices decreased with increasing viscosity, whereas in a centrifugal nozzle, capacity was seen to increase somewhat with viscosity as long as atomization was effective. Larcombe (*13*), on the other hand, found that for an increase in viscosity, a slightly higher pressure was required to maintain a constant flow rate. Spray cone angle, according to Glendenning, decreased as viscosity increased.

Of all the liquid properties, viscosity is probably the most significant because it can vary over so extreme a range.

The tedious counting procedure involved in the determination of drop-size-distribution data has usually limited the development of precise and complete relationships between drop size and the variables of nozzle design, operation, and liquid properties. Lee (*15*), in 1932, counted nearly 180,000 drops in an effort to determine the effect upon drop size of orifice diameter, ratio of orifice length to diameter, injection pressure, and chamber pressure for plain injection nozzles. He also made a few runs with impact-type nozzles but reported only a single run for a centrifugal nozzle.

Nukiyama and Tanasawa (*20*), on the basis of a large number of runs with pneumatic atomizers, developed an empirical equation for mean droplet size which was modified as follows by Lewis et al. (*16*) in an attempt to correlate the data for pressure nozzles:

$$D_{VS} = 157\sqrt{\sigma/p} + 597\left(\frac{\mu}{\sigma\rho}\right)^{0.45}\left(\frac{Q_l}{k_X d_o\sqrt{p/\rho}}\right)^{1.5} \quad (1)$$

In applying this equation to the T-type nozzle data of Houghton (*11*) and to the injection-nozzle data of Lee (*15*), fair agreement was attained between actual and computed values of D_{VS}. However, k_X was found to differ greatly for the two sets of data.

An equation for representing drop-size distribution was proposed by Nukiyama and Tanasawa as follows:

$$\frac{dN}{dD} = aD^p e^{-bD^q} \quad (2)$$

where N = number of drops with diameters between zero and D
D = diameter of an individual drop, microns

Experimental data are necessary to establish the values of the constants in Equations (1) and (2) for any given type of nozzle.

One of the more extensive investigations of drop size was the work of Longwell (*17*) on centrifugal pressure nozzles for oil burners. He obtained the following empirical equations for mean drop size and size distribution from drop-size data for various oils:

Mean drop size:

$$\frac{D_{V50}(\sin\theta/2)}{d_o/2} = \frac{k_L\nu^{0.395}}{p^{0.375}} \quad (3)$$

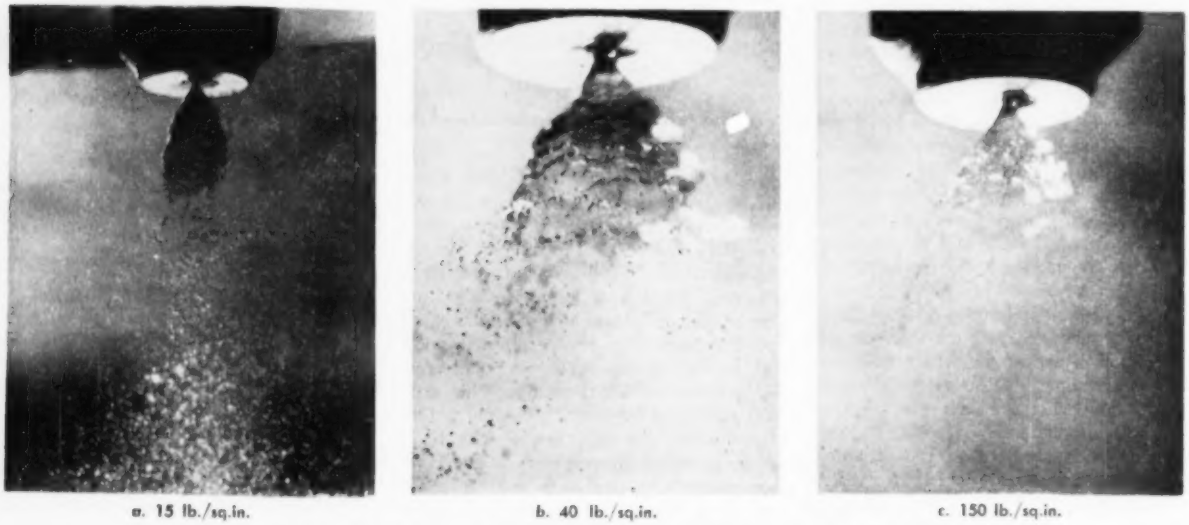
Drop-size distribution:

$$R = e^{-0.693(D/D_{V50})^{k'_L}} \quad (4)$$

where

R = weight fraction of sample above size D,
k_L' = measure of uniformity, constant

For fuel oil, Longwell established a value of 0.72 for k_L and a value of 2.8 for k_L'. Later work by Pierce (*22*) on specially designed centrifugal nozzles gave higher values for k_L in the neigh-



a. 15 lb./sq.in. b. 40 lb./sq.in. c. 150 lb./sq.in.

Fig. 1. High-speed photographs of dyed-water spray from a centrifugal nozzle. d_o = 0.031 in.

borhood of 1.8, while in applying Houghton's data to Equation (3), Pierce found k_1 to vary from 3.5 to 9.9.

The Mechanism of Atomization

Since Rayleigh's pioneer work in 1878, on the breakup of liquid jets (*24*), the actual mechanism of atomization has been a phenomenon of interest to many investigators.

Weber (*31*) extended Rayleigh's analysis to the breakup of viscous liquids under forces of surface tension and air resistance, while Castleman (*3, 4*), in applying the same analysis to high velocity disturbances, pointed out the similarity between pneumatic or air-stream atomization and pressure injection. Castleman further postulated the formation of ligaments at the liquid-gas interface which, under the effect of surface tension, collapse into droplets. Lee and Spencer (*14*), by means of photomicrographic studies of fuel sprays, observed that ligament formation is controlled by the relative velocity between air and liquid. For various constant values of $(\mu/\sqrt{\rho\sigma d_o})$, Ohnesorge (*21*) found jet stability to be a function of Reynolds number. For low values of Reynolds number, Rayleigh vibrations occurred; at intermediate values, jets disintegrated by means of helicoidal vibrations, while at high Reynolds numbers, complete atomization occurred at the orifice.

In contrast to the plain jet, the centrifugal nozzle tends to produce an unstable conical sheet of liquid which breaks up into droplets a short distance from the orifice. Figure 1, taken in this study, illustrates how undulatory disturbances in the cone eventually result in the collapse of the sheet into individual droplets. Comparison of the three high-speed photographs reveals that breakup occurs nearer the orifice as pressure is increased. This behavior is analogous to that cited by Ohnesorge for plain jets.

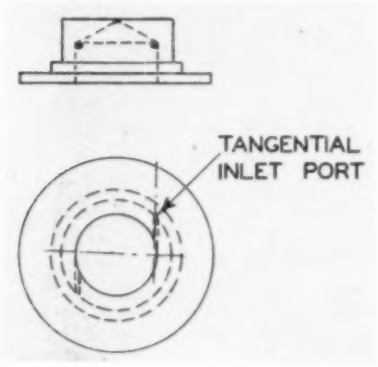


Fig. 2. Whirl chamber for Marley atomizing nozzle.

Experimental Equipment and Procedures

Requirements of the equipment for this study were (1) a method for controlling and varying the pressure and flow rates of the pressure nozzles, (2) means for varying specific features of nozzle design, and (3) methods for measuring the resultant spray characteristics.

The Marley atomizing nozzle was selected to study weight flow patterns on the basis of its adaptability to systematic variations in design. A number of brass whirl chambers (Fig. 2) were fabricated in which the entrance angle, β, and the number of inlet passages were varied from 0° to 90° and from 1 to 4, respectively.

Several Spraying Systems grooved-core spray-drying nozzles were used to study drop-size distribution. Figure 3 shows the configuration of the grooved core. Variation in the cross-sectional area of the grooves permitted systematic changes in the tangential velocity component of the liquid within the nozzle.

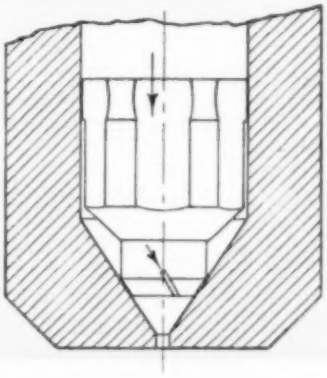


Fig. 3. Spraying Systems grooved-core nozzle.

Two other nozzles, a Spraco *T*-type hollow-cone nozzle and a Spraco solid-cone nozzle, were tested at low pressures.

Pressures up to 1500 lb./sq.in. were obtained with compressed nitrogen applied to a reservoir cylinder containing the liquid to be atomized as shown in Figure 4. The liquid line, ¼-in. high-pressure piping, extended to within an inch of the bottom of the reservoir. The line and nozzle were placed so that the spray was directed downward in the center of a plywood enclosure. Nitrogen from an adjacent cylinder was released through a high pressure reducer valve into an annular space around the liquid line. A bleeder valve was inserted between the two vessels so that rapid reductions in pressure in the system could be achieved.

Nozzle capacity was measured by placing the nozzle into a metal sleeve which directed liquid for a given length of time into a volumetric measuring vessel.

The second spray property determined was the weight flow distribution; i.e., the spatial density of liquid at any point beneath the nozzle expressed as the cone angle including any given fraction of the total volume being atomized. This was determined by collecting the spray in sheet-metal cylinders mounted annularly upon a circular base plate and so arranged that at a vertical distance of 5 in. between the nozzle orifice and the tops of the cylinders, each annular compartment would subtend an even fraction or multiple of a steradian, the solid angle measured radially from the orifice. (One steradian subtends an area of r^2 on the surface of a sphere of radius r.) The unit of the steradian was chosen because, for a given intensity of flow in space, the rate of flow per steradian would not change, whereas flow rates per degree of *plane* angle or per unit of horizontal distance from the nozzle axis would vary as one moved in relation to the nozzle axis. Ports cut in the base plate of the apparatus permitted drainage from each compartment into a graduate. Uniformity of spray pattern was determined by exposing only one quadrant of the weight-distribution apparatus at a time.

The final characteristic of sprays determined quantitatively in this investigation was drop-size distribution, i.e., the number of droplets which occurred within each of several specified size

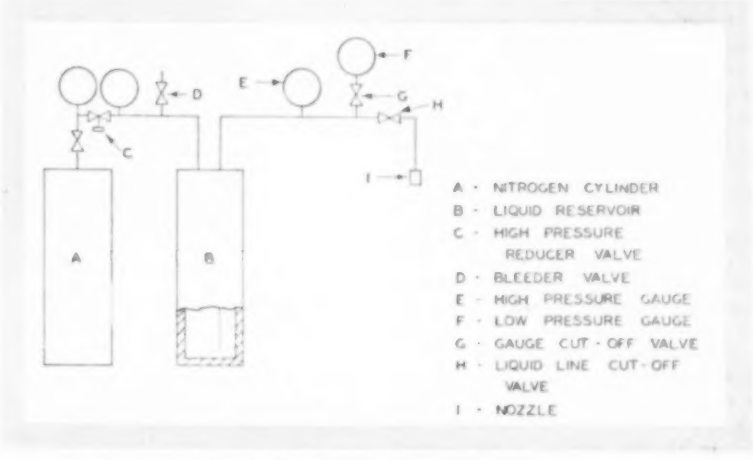


Fig. 4. Flow diagram of pressure system.

ranges. The number of size ranges should be sufficient to approximate the actual distribution. The accuracy also depends on the total number of droplets reported. For the purpose of illustration, consider a distribution to be represented graphically as the percentage of droplets under a given size plotted against that size. If, then, it is specified that this cumulative-distribution curve should not deviate from the actual distribution at any point by more than an *absolute* error equal to one per cent of the total number of droplets, it can be shown (*18*) that 18,500 droplets must be counted to fulfill this requirement 95% of the time. Figure 5 shows the absolute deviation which may be expected from an actual cumulative distribution curve as a function of the number of droplets counted. The number of droplets required to ensure a given accuracy depends also on the choice of sampling locations. If the locations are not chosen judiciously with respect to the greatest volume of spray, then the required counts may be considerably greater than suggested by Figure 5. At best, the total count for any single spray should be on the order of several thousand drops if the error is to be confined to a small percentage.

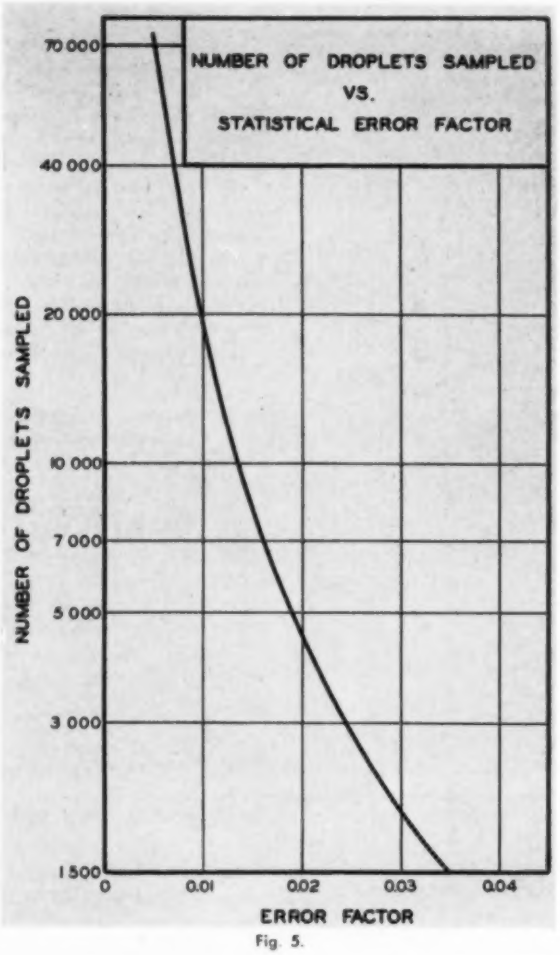


Fig. 5.

The drop-sampling method chosen was a modification of Rupe's procedure (*25*) in which glass-bottom cells filled with Stoddard solvent were exposed to a spray of dyed water. A 2½% solution of nigrosine in water was sufficient to provide perfectly opaque droplets which, when photographed, appeared as transparent images on the negative. Surface tension measurements at 73° F. yielded a value of 62.5 dynes/cm. for the dyed solution as contrasted to 72.2 dynes/cm. for pure water. Thus drop sizes obtained with the dyed water might be slightly smaller than for pure water. When it was desired to vary the liquid viscosity, the dyed water was mixed with appropriate quantities of glucose.

The cells used in collecting the spray were cut from brass with the dimensions shown in Figure 6. The bottoms, cut from optically flat glass, were coated periodically with G.E. Dri-film on the upper surface to prevent droplets from spreading. The use of Stoddard solvent was recommended by Rupe (*25*) not only because of its immiscibility with water but also because its density permitted water droplets to sink through the solvent and remain suspended as practically perfect spheres, barely touching the cell bottom.

Exposure of the cells was accomplished by means of a shutter assembly wherein the cell was placed in a box-like enclosure, and slides with various-sized aperture slits were moved rapidly over the cell. By means of a graduated metal runway, the shutter assembly was positioned at any desired distance from the nozzle axis. After exposure, the cells were completely filled with solvent and covered with glass so as to eliminate any meniscus effect. Photomicrographs of the droplets were made on a high contrast cut film with a photomicrographic camera. The choice of magnification depended on the size of the droplets being photographed, and for the range of sizes involved in this investigation, a magnification of 35X or 50X was found to be satisfactory. A blue filter was used in the optical system to minimize chromatic aberration and ensure distinct images.

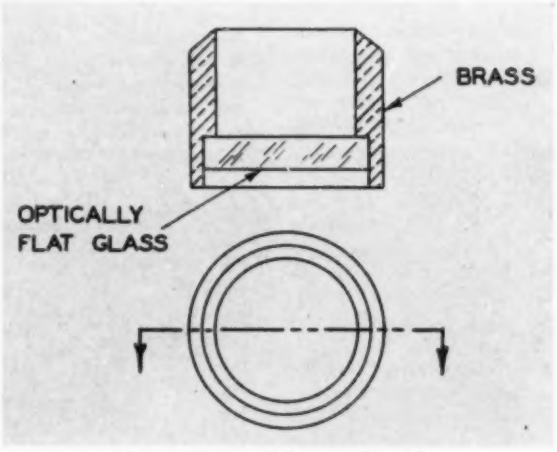


Fig. 6. Diagram of drop sampling cell.

Techniques described above were designed to provide negatives suitable for use with an electronic drop-size distribution analyzer described by Adler, Mark, Marshall, and Parent (*1*). However, the size-distribution data presented in this paper were evaluated prior to the final development of the analyzer and were determined from a visual count of

prints made from 5-in. × 7-in. negatives (Fig. 7). With the aid of a magnifying glass and an engineering rule drops were counted at a rate of about 1500/hr. To maintain a reasonable counting rate, it was necessary to employ two individuals; one to measure and count, and the other to record the data. A tape recorder was sometimes utilized to record a count.

TREATMENT OF DATA

Weight Flow Distribution

The weight flow distribution data were plotted as the percentage of liquid falling within a given solid angle, ω, vs. ω, yielding a curve of the type shown in Figure 8. The plane cone angle, θ, corresponding to any value of ω is related to ω as follows:

$$\theta = 2\cos^{-1}(1 - \omega/2\pi) \qquad (5)$$

locations by laying off the desired number of sampling zones along the ordinate axis. This method of choosing sampling points assumed that the drop-size distribution at the mid-point of a zone was representative of the distribution for the whole zone. Since the diameter of a collection cell was of the order of magnitude of a zone width, this assumption seemed justified. The vertical distance between cells and nozzle orifice was kept the same as the vertical distance between the orifice and the weight flow distribution apparatus, in order that the equivolume zones could be determined from weight flow data. A suitable sample ordinarily was secured by exposing two collection cells at each point.

Particle-Size Distribution Data

One method of particle-size representation commonly used is one wherein the

$$f = \frac{\Sigma f_i}{s\sqrt{2\pi}}\, e^{\frac{-(X-M)^2}{2s^2}} \qquad (7)$$

where

f = frequency of observations of value X
Σf_i = total number of observations
M = a constant, value of X at maximum value of f
s = a constant usually termed the standard deviation

Data satisfying Equation (7) will plot as a straight line on normal probability paper. The resulting line can be characterized by two parameters, a slope and an intercept. Ordinarily, it is convenient to choose as an intercept the volume median diameter, D_{V50}, corresponding to 50% on the cumulative volume.

The slope of the plot, on the other hand, is a measure of spray uniformity

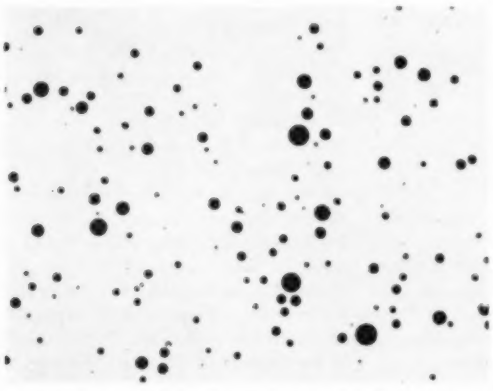


Fig. 7. Specimen photomicrograph of collected dyed drops.

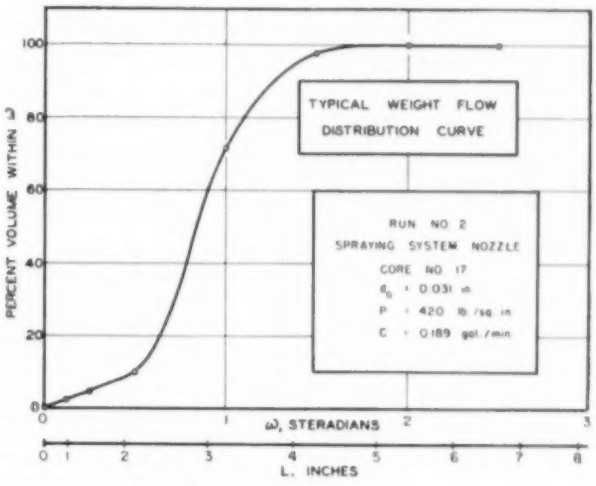


Fig. 8.

Similarly, the relationship between ω and the linear distance, L, measured outward from the nozzle axis at a distance, H, below the nozzle orifice is

$$L = \frac{H\sqrt{(4\pi - \omega)}}{(2\pi - \omega)} \qquad (6)$$

Weight flow data were used in determining the locations of drop-sampling points as follows:

For each run, six cell locations were determined such that each position corresponded to the mid-point by volume of a zone representing one sixth of the total volume of the spray. Then, after the droplets sampled in each zone were counted, the partial volumes of droplets for each zone were adjusted or weighted to the same volume of spray.

The cumulative curve of the type shown in Figure 8 was used to determine the mid-points for sample cell

number or the fraction of the total number of droplets in a given size class is plotted against that size class. Frequently, however, a given size class may contain a high percentage of the total number of the droplets in the spray, but this may represent only *one* or *two per cent* of the total volume of the spray. This usually occurs for the size range including the smallest drops. In this case, a representation based on volume or surface area is usually preferred. Such was the case in this study, and frequency curves were plotted in which the volume associated with a given range of droplet sizes was plotted against the size range. In corresponding cumulative plots, the percentage of total volume associated with droplets under a given size was plotted against that size.

A normal distribution of drop sizes would satisfy the normal probability equation:

and is related to s, the standard deviation, in Equation (7). For a linear probability plot, s is computed from $s = D_{V84.13} - D_{V50}$, where $D_{V84.13}$ refers to the drop diameter corresponding to 84.13% less than size.

It is not logical to expect a physical process, such as atomization, to obey the normal distribution law, Equation (7), since this law would predict the existence of drops not only much larger than the mean size, but also of drops whose diameters are negative. Therefore, it is to be anticipated in atomization studies that drop-size distribution will follow some law which is compatible with the physical process of liquid breakup. Recognition of the need for adequate size distribution-laws for physical disintegration processes has been made by several workers (*11a*, *19a*), and various attempts have been made to develop distribution laws which take into account

physical limitations in the atomization process such as limits on the upper and lower drop sizes. The problem of deriving from theory a distribution law for atomization requires a knowledge of all the factors causing liquid breakup and the variations of their interdependence. At present, this appears to be an insurmountable problem.

In this study, the drop-size-distribution law obtained was totally empirical, and no attempt was made at this stage of the study to justify it from theoretical consideration. Further, it is not proposed that the drop-size correlation observed in this work is necessarily a general one for all pressure nozzles.

Experimental results and correlations will be presented in Part II.

Notation

A_G = cross-sectional area of a single groove in a grooved-core-type nozzle, sq.in.
a = constant in the Nukiyama-Tanasawa equation for drop-size distribution
b = constant in the Nukiyama-Tanasawa equation for drop-size distribution
C = capacity of nozzle, gal./min.
D = diameter of an individual droplet, μ
D_m = drop diameter corresponding to maximum value of N
D_{VSD} = volume median diameter, μ
D_{VS} = diameter of a droplet whose ratio of volume to surface area is equal to that of entire spray, μ
d_o = orifice diameter, in.; jet diameter, in.
$f_D(V_t)$ = function relating D_{VS} to V_t for constant V_v and d_o
$f_\theta(V_t)$ = function relating θ_{90} to V_t for constant V_t and d_o
$f_s(V_v)$ = function relating s to V_v for constant V_t and d_o
$g_D(V_t)$ = function relating D_{VS} to V_t for constant V_v and d_o
$g_\theta(V_t)$ = function relating θ_{90} to V_t for constant V_v and d_o
$g_s(V_t)$ = function relating s to V_t for constant V_v and d_o
H = vertical distance between nozzle orifice and sampling apparatus, in.
$h_D(d_o)$ = function relating D_{VS} to d_o for constant V_v and V_t
$h_\theta(d_o)$ = function relating θ_{90} to d_o for constant V_v and V_t
$h_s(d_o)$ = function relating s to d_o for constant V_v and V_t
k_L = constant in Longwell's equation for median drop size
k_L' = constant in Longwell's equation for drop-size distribution
k_N = constant in modified Nukiyama-Tanasawa equation for mean drop size
$K = C/\sqrt{p}$
L = linear distance from central nozzle axis, in.
M = value most frequently observed in a normal probability distribution
N = number of drops
N_i = number of drops in i-th size class
N_G = number of grooves in a grooved-core-type nozzle
p = nozzle gauge pressure, lb./sq.in.; also constant in the Nukiyama-Tanasawa equation, Equation (2), for drop-size distribution
Q_t = volume rate of flow of liquid in an atomizer
q = constant in Nukiyama-Tanasawa equation for drop-size distribution
R = weight fraction of spray sample above size, D, in Longwell's equation for drop-size distribution
s = standard deviation in a normal probability distribution; also index of uniformity, volume basis
V_t = tangential velocity component, ft./sec.
V_t' = effective tangential velocity, ft./sec.
V_v = vertical velocity component, ft./sec.

Greek Symbols

α = angle made by grooves with the horizontal in a grooved-core-type nozzle
β = angle made by inlets with inner wall of a whirl chamber
γ = liquid kinematic viscosity, stokes
θ = spray cone angle, degrees
θ_{90} = plane angle subtending 80% of total spray, degrees
μ = liquid viscosity, poise; also denotes micron as unit of measure
η_A = per cent of input power used to create additional surface area
ρ = density of liquid, g./cc.
σ = surface tension, dynes/cm.
ω = solid cone angle, steradians

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Part II will appear in an early issue.

Annual Thesis Index

Several requests have come to this office for copies, microfilms, photostats, both positives and negatives, of theses listed in the classification on page 47 of the January issue of "C.E.P."

No copies are available in this office and no orders are taken here. Inquiries must be directed to the university where the work was accomplished, and given in our listing right after the name of the prospective Ph.D., or to other sources mentioned.

Heat Capacity of Organic Liquids

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A correlation is presented to predict the heat capacity of a number of liquids as a function of their structural parachor and molar refraction values without experimental data. Watson's expansion factor has been extended to relate the variation of liquid heat capacities with temperature and pressure. A proposed relationship between heat capacity and expansion factor permits estimation of heat capacity for liquids at any condition from a single known value.

Heat capacity of liquids is often necessary information for chemical engineering calculations and design. However, available data are meager. Owing to difficulties in dealing with the liquid state in general, little progress has been made toward prediction of liquid heat capacities from theory. Empirical correlations in the literature are often restricted to specific classes of compounds and sometimes require knowledge of other unavailable physical properties.

Hougen and Watson (*15*) recommended Kopp's rule for prediction of liquid heat capacities, and Wenner's values for atomic heat capacities. Atomic heat capacity ignores the constitutive properties of a molecule, hence, at best it is only a rough approximation. Trouton's rule, modified by Hildebrand, predicts liquid heat capacities (*12*). Its application, however, requires the molal latent heat of vaporization and the normal boiling point. Watson (*32*) derived thermodynamic expressions relating heat capacities of a saturated liquid to that of its vapor. Aside from the difficulties in using this method, its practical value is limited, since only liquids at their boiling points can be used.

Heat capacities of liquid petroleum fractions have been studied (*4, 14, 19-21, 24-29*). Correlations for these liquids have been reported (*3, 8, 31*) and verified (*9, 33*). As such, they can hardly be expected to be applicable to compounds other than hydrocarbons.

Recently considerable work has been done in the field of the liquid state (*7, 13, 16-18*). Debye (*5*) treated the liquid state as a closely approached crystalline state. Devonshire (*6*) calculated the heat capacities of liquids from their intermolecular forces by statistical mechanical methods. Golik (*10, 11*) working on Eyring's theory, expressed the heat capacities of monatomic liquids in terms of the temperature dependence of the liquid structure and the energy of evaporation. Bauer, Magat and Surdin (*1*) found the heat capacity of a liquid at the critical point to be different from that of its corresponding vapor. Bhagavantam (*2*) employed the Raman effect in estimating liquid heat capacities by treating the liquid state as being an intermediate between the solid and the gaseous state. Whereas these works do throw light on the nature of the liquid state, it is clear that they are still in so early a stage of development that no practical value can yet be derived therefrom.

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Parachor and Molar Refraction

Meissner (*22*) correlated the critical constants with the parachor and molar refraction. The parachor is defined by Sudgen (*30*) as:

$$P = \frac{M\sigma^{1/4}}{\rho_l - \rho_v} \qquad (1)$$

Molar refraction is calculated from the Lorentz-Lorenz equation:

$$[R_\lambda] = \frac{M}{\rho_l} \cdot \frac{n_\lambda^2 - 1}{n_\lambda^2 + 2} \qquad (2)$$

Meissner's correlation is convenient to use since both the parachor and molar refraction of any substance can be calculated from the atomic and structural values. A summary of the values, taken from Meissner's article, is presented in Table 1.

According to Meissner, the physical significance of the parachor is that the ratio of the parachors of two substances is equal to the ratio of their molal liquid volumes at equal surface tension under such temperatures that the vapor densities are negligible. Molar refraction, on the other hand, represents the actual volume of the molecules in one mole of substance. It follows that the ratio of $(R)/(P)$ may be regarded as the fraction of the total liquid volume occupied by the molecules themselves, under conditions of equal surface tension. Furthermore, since surface tension is closely related to internal pressure and the latter to the intermolecular force field densities, it is reasonable to expect the $(R)/(P)$ ratio to be a measure of the intermolecular attractive forces.

Meissner's correlation leads the authors to suspect that the same type of correlation can be applied to heat capacities of liquids, since the heat capacity

Table 1.—Atomic and Structural Values—Parachors and Molar Refractions (22)

	Parachor	Refraction (Sodium D Line)
C	9.2	2.418
H	15.4[1]	1.100
—CH_2—	40.0	4.618
O (hydroxyl)	20	1.525
O (ether)	20	1.643
O (carboxyl)	39[2]	2.211[2]
F	25.5	....[4]
Cl	55	5.967
Br	69	8.865
I	90	13.90
N (primary amine)	17.5	2.322
N (secondary amine)	17.5	2.502
N (tertiary amine)	17.5	2.840
N (nitrile)	55.5[3]	5.516[3]
S	50	....[4]
P	40.5	....[4]
3-Membered ring	12.5	0
4-Membered ring	6	0
5-Membered ring	3	0
6-Membered ring	0.8	0
7-Membered ring	–4.0	0
Double bond	19.0	1.733
Semipolar double bond	0	1.733
Triple bond	38	2.398
Singlet linkage	–9.5	....

Parachor Strain Constants

(R = hydrocarbon radical, X = negative group)

3	Carbonyl in ring
0	RCH_2X; R•CHO; R•CO•R; RCH_2R; RNH_2; NO•R; NOOR; R_2SeO
–3	$RCHX_2$; RCOOH; R•CO•OR; R•COCl; R_2CHX; R_2CH•R; $RCONH_2$; RO•CO•OR; RO•CO•Cl; R•SO•OR; RO•SO•OR; R_2NH; NOCl; NO_2R; NO_2OR; N_2O, azides; RSeOOH
–6	$R•CX_3$; R_2CX; Cl•CO•Cl; R•SO_2•Cl; R_2CR; RSO_2•R; RO•SO_2•R; RO•SO_2•OR; R_3N; NCl_3; NO_2Cl; PX_3; R_3P; $PO(OR)_3$; BX_3; AsX_3; SbX_3
–9	CX_4; R_4C; SCl_4; SO_2Cl_2; $NOCl_3$; $POCl_3$; SiX_4; SnX_4
–12	$SOCl_4$; NCl; PCl_5; $SbCl_5$
–15	SCl_6

[1]Hydrogen on bromine has a parachor of 16.4; on chlorine 12.8; on oxygen; on nitrogen 12.5.
[2]Includes allowance for double bond
[3]Includes allowance for triple bond
[4]Value depends on type of compound

is also related to the intermolecular forces. Furthermore, the empirical relationships thus derived will probably hold true for all substances whose structures are alike, i.e., applicable to any one homologous series.

Proposed Correlation

Since both the parachor and molar refractions are virtually temperature-independent, and heat capacities vary with temperature, it is necessary to choose an arbitrary temperature level at which the heat capacities are compared. Because the majority of literature values are reported at or near 20° C., this is chosen as the basic temperature.

The parachor and molar refractions are calculated from the atomic and structural values given in Table 1. Heat capacities are mostly taken from the International Critical Tables. After exhausting the useful heat-capacity values in the literature, it was found that the following equation correlates satisfactorily.

$$C = \frac{P + B}{AR} \qquad (3)$$

A few sample curves plotted as the product of RC vs. P are given in Figure 1 to illustrate the method of correlation. Values for the empirical constants are given in Table 2. Calculations, together with the comparison of actual values with calculated values, are summarized in Table 3. An illustrative example is given in Table 4.

Figure 1 and Table 3 disclose that the correlation is satisfactory, with a mean discrepancy of 2% and a maximum not exceeding 5%. Some of the experimental values are doubtful. Furthermore, sometimes only a temperature range for the heat capacity of a given substance can be found. In still other cases, the heat capacity at 20° C. can be determined only by interpolation. All considered, the empirical equation probably will give values which do not much exceed the experimental error.

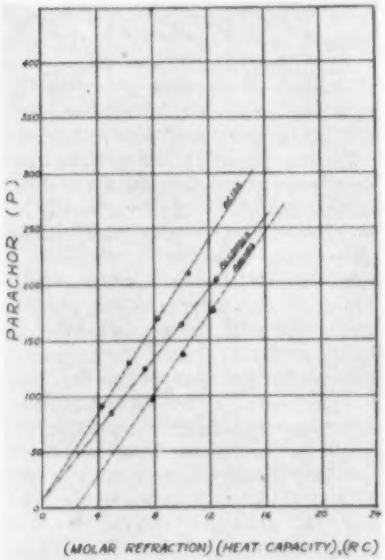

Fig. 1. Relation between the parachor and the product of molar refraction and heat capacity at 20° C.

Table 2.—Values of "A" and "B" at 20°C.

Class	A	B
Paraffinic hydrocarbons	18.5	24
Acids	19.5	–5.8
Alcohols	15.9	–5.8
Esters	20.25	–5.8
Ketones	15.8	–18
Nitriles	16.5	–20
Amines	17.8	45
Monochlorides	17.5	–37
Dichlorides	26	–21
Trichlorides	20	–89
Chloroacetates	18	–58
Dichloroacetates	20.6	–76
Trichloroacetates	22.6	–94
Isoalcohols	21.5	76
Aromatic hydrocarbons	17.3	–49
Benzoates	15.75	–97
Phenyl ethers	16.75	–41
p—Cresyl ethers	14.6	–88

Variation of Liquid Heat Capacity with Temperature and Pressure

Heat capacities of petroleum liquids have been successfully correlated with density (*3, 8, 31*) and liquid densities correlated with the "expansion factor" (*15, 32*). Watson found that the quotient of the density divided by the expansion factor is essentially constant for all liquids. The expansion factor, in turn, when expressed as a function of the reduced temperature and pressure,

Table 3. — Heat Capacities—Actual vs. Calculated at 20°C.

Compound	P	R	C (actual)	C (calc.)	% Error
n—Butane	190.8	20.67	0.549	0.563	2.6
n—Pentane	230.8	25.29	0.558	0.544	2.5
n—Hexane	270.8	30.20	0.527	0.528	0.2
n—Heptane	310.8	34.82	0.491	0.520	2.8
n—Octane	350.8	39.44	0.505	0.514	1.8
n—Nonane	390.8	44.06	0.503	0.509	1.2
n—Decane	430.8	48.68	0.493	0.505	2.4
Formic acid	90.6	8.35	0.512	0.521	1.7
Acetic acid	130.6	12.97	0.488	0.493	1.0
Proprionic acid	170.6	17.59	0.473	0.481	1.7
n—Butyric acid	210.6	22.21	0.473	0.473	0.0
Methanol	85.4	8.34	0.600	0.601	0.8
Ethanol	125.4	12.96	0.569	0.581	1.9
n—Propanol	165.4	17.58	0.571	0.571	0.0
n—Butanol	205.4	22.20	0.563	0.566	0.5
Methyl formate	139.0	12.97	0.519	0.507	2.3
Ethyl formate	179.0	17.59	0.508	0.486	4.3
n—Propyl formate	219.0	22.20	0.459	0.474	3.3
n—Butyl formate	259.0	26.82	0.459	0.466	1.5
Methyl acetate	179.0	17.57	0.468	0.487	4.1
Ethyl acetate	219.0	22.20	0.457	0.474	3.7
n—Propyl acetate	259.0	26.82	0.459	0.466	1.5
Methyl propionate	219.0	22.20	0.459	0.474	3.3
Ethyl propionate	259.0	26.82	0.457	0.466	2.4
n—Propyl propionate	299.0	31.44	0.459	0.460	0.2
n—Butyl propionate	339.0	36.06	0.459	0.456	0.6
Methyl butyrate	259.0	26.82	0.459	0.466	1.5
Ethyl butyrate	299.0	31.44	0.457	0.460	0.7
n—Propyl butyrate	339.0	36.06	0.459	0.456	0.6
n—Butyl butyrate	379.0	40.68	0.459	0.453	1.3
Dimethyl ketone	159.0	16.07	0.514	0.488	5.1
Methyl ethyl ketone	199.0	20.68	0.549	0.554	0.9
Methyl butyl ketone	279.0	29.92	0.553	0.554	0.2
Diethyl ketone	239.0	25.30	0.555	0.553	0.4
Dipropyl ketone	319.0	34.54	0.550	0.551	0.2
Acetonitrile	120.1	11.25	0.542	0.539	0.6
Propionitrile	160.1	15.87	0.538	0.535	0.6
Butyronitrile	200.1	20.49	0.548	0.533	2.7
Valeronitrile	240.1	25.11	0.521	0.531	1.9
Methylamine	97.9	10.24	0.765	0.783	2.4
Ethylamine	137.9	14.86	0.691	0.692	0.1
Propylamine	177.9	18.48	0.663	0.678	2.3
Methyl chloride	110.4	11.68	0.371	0.359	3.2
Ethyl chloride	150.4	16.30	0.369	0.397	7.6
Propyl chloride	190.4	20.92	0.404	0.419	3.7
Butyl chloride	230.4	25.54	0.452	0.433	4.2
Methylene dichloride	147.0	16.54	0.287	0.292	2.0
Ethylene dichlorode	187.0	21.16	0.301	0.302	0.3
Chloroform	183.6	21.42	0.226	0.221	2.2
Trichloroethane	223.6	26.04	0.266	0.258	3.0
Methyl chloroacetate	212.6	22.45	0.383	0.382	0.3
Ethyl chloroacetate	252.6	27.07	0.399	0.399	0.0
Propyl chloroacetate	292.6	31.69	0.415	0.412	0.7
Methyl dichloroacetate	249.2	27.32	0.311	0.318	2.2
Ethyl dichloroacetate	289.2	31.94	0.330	0.335	1.5
Propyl dichloroacetate	329.2	36.56	0.342	0.337	1.5
Methyl trichloroacetate	285.8	32.19	0.268	0.263	1.9
Ethyl trichloroacetate	325.8	36.81	0.286	0.279	2.4
Propyl trichloroacetate	365.8	41.42	0.298	0.291	2.7
Isopropyl alcohol	162.4	17.58	0.602	0.631	4.8
Isobutyl alcohol	202.4	22.20	0.603	0.583	3.3
Isoamyl alcohol	242.4	26.72	0.549	0.554	0.9

(Continued on page 178)

Table 3.—(Continued)

Compound	P	R	C (actual)	C (calc.)	% Error
Benzene	205.4	26.31	0.340	0.344	1.2
Toluene	245.4	30.93	0.364	0.367	0.8
Ethyl benzene	285.4	35.54	0.402	0.385	4.2
Propyl benzene	325.4	39.16	0.400	0.408	2.0
Butyl benzene	365.4	43.78	0.428	0.418	2.3
Methyl benzoate	310.6	37.18	0.363	0.365	0.5
Ethyl benzoate	350.6	41.80	0.389	0.385	1.0
Propyl benzoate	390.6	46.42	0.399	0.402	0.7
Methyl phenyl ether	265.4	32.45	0.406	0.412	1.5
Propyl phenyl ether	345.4	41.68	0.429	0.437	1.9
Methyl p—cresyl ether	305.4	37.06	0.406	0.402	1.0
Ethyl p—cresyl ether	345.4	41.68	0.429	0.424	1.2

is approximately the same for all substances (*32*). It suggests then, that some relationship may exist between the expansion factor and the heat capacity. Since the determination of the former requires only a knowledge of the critical properties of the substance, this relationship would present a convenient method by which the heat capacity of a liquid at one temperature and pressure can be predicted when that at another temperature and pressure is known. In most of the correlations of the heat capacities of hydrocarbons, the heat capacity varies inversely as the first power or the square root of the density at the same temperature. The following form of correlation would therefore be expected:

$$C\omega^a = b \qquad (4)$$

Owing to the lack of data in the literature, this proposed relationship cannot be explored. Data investigated are listed in Table 6 and the values of the empirical constant b are listed in Table 5. A value of *2.8* for a applies satisfactorily to the majority of substances. It is interesting to note that the value of b is approximately constant for all alcohols, thus one is in a position to make a good estimation of the heat capacity of a compound if one value of a member of its homologous series is known at one temperature and pressure. This known factor, together with the expansion factor calculated from Watson's correlation enables a calculation of the constant b. Once the value of b is known, the heat capacity at any other temperature and pressure within the Watson correlation range can be estimated from Equation (4).

Data on the variation of heat capacity with pressure are even more scarce in the literature. Only those of butane were investigated. As shown in Table 6, the correlation appears to agree with the trend.

Notation

A, B = constants in Equation (3)
a, b = constants in Equation (4)
C = heat capacity, calories g. cal./° C.
M = molecular weight, g.
n = refractive index
P = parachor
R = molar refraction

Greek Letters

σ = surface tension, dynes/cm.
λ = wavelength of monochromatic light
ρ_l = density of liquid, g./cc.
ρ_v = density of vapor, g./cc.
ω = Watson's expansion factor

Table 4. — Example—Diphenylamine $C_6H_5NHC_6H_5$

12 Carbon atoms	(12)(9.2) =	110.4	(12)(2.148) =	29.016
10 Hydrogen (to carbon)	(10)(15.4) =	154.0	(10)(1.100) =	11.000
1 Hydrogen (to nitrogen)		12.5		1.100
1 Nitrogen (secondary amine)		17.5		2.502
2 6-membered ring	(2)(0.8) =	1.6		0
Strain constant (R_2NH)		−3		.....
		293.00		43.618

From Table 2, for amines,

$A = 17.8$ $B = 45$

Equation (3),

$$c = (293 + 45)/(17.8)(43.618) = 0.435$$

The nearest experimental data are reported to be 0.437 at 54°C.

Table 5.—Value of b in Equation 4

Compound	b
Methanol	0.00184
Ethanol	0.00177
Propanol	0.00185
Isopropanol	0.00192
Butanol	0.00187
Isoamyl alcohol	0.00194
Benzene	0.00133
Toluene	0.00136
Bromobenzene	0.00090
Chlorobenzene	0.00112
Aniline	0.00182
Carbon tetrachloride	0.00067
Chloroform	0.00076
n—Heptane	0.00160
n—Butyric acid	0.00186
Acetone	0.00162
Ether	0.00140

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Table 6.—Heat Capacities as a Function of Watson's Expansion Factor

Compound	Pres. (atm.)	Temp. (°C.)	C	ω	$\omega^{2.8}$	$C\omega^{2.8}$	% Deviation from Mean
Methanol	1	0	0.568	0.1296	0.00327	0.00186	2.2
	1	20	0.600	0.1264	0.00309	0.00185	0.5
	1	40	0.617	0.1230	0.00283	0.00175	3.8
Ethanol	1	−50	0.473	0.1386	0.00395	0.00187	5.0
	1	0	0.536	0.1303	0.00331	0.00177	0.0
	1	20	0.573	0.1269	0.00309	0.00177	0.0
	1	25	0.582	0.1263	0.00305	0.00177	0.0
	1	50	0.653	0.1220	0.00276	0.00180	1.7
	1	100	0.825	0.1120	0.00218	0.00180	1.7
	1	150	1.052	0.1000	0.00159	0.00167	5.6
Propanol	1	−50	0.457	0.1400	0.00407	0.00186	1.1
	1	−25	0.481	0.1360	0.00376	0.00181	1.6
	1	0	0.527	0.1320	0.00345	0.00182	1.1
	1	25	0.587	0.1280	0.00317	0.00186	1.1
	1	50	0.655	0.1240	0.00279	0.00183	0.5
Isopropanol	1	−50	0.473	0.1380	0.00389	0.00184	3.2
	1	0	0.564	0.1295	0.00327	0.00184	3.2
	1	50	0.742	0.1212	0.00271	0.00201	5.8
Butanol	1	−33.3	0.453	0.1388	0.00398	0.00180	3.2
	1	2.3	0.526	0.1335	0.00356	0.00188	1.1
	1	19.2	0.563	0.1308	0.00336	0.00189	1.6
	1	30	0.582	0.1293	0.00324	0.00188	1.1
Isoamyl alcohol	1	0	0.502	0.1352	0.00369	0.00185	5.1
	1	20	0.535	0.1324	0.00347	0.00186	4.6
	1	30	0.571	0.1308	0.00336	0.00192	1.5
	1	47.9	0.662	0.1284	0.00319	0.00211	8.2
	1	75.5	0.687	0.1240	0.00289	0.00198	1.5
Benzene	1	5	0.390	0.1332	0.00354	0.00138	3.8
	1	10	0.394	0.1324	0.00347	0.00137	3.0
	1	20	0.407	0.1308	0.00336	0.00137	3.0
	1	40	0.423	0.1289	0.00322	0.00136	2.3
	1	60	0.446	0.1250	0.00295	0.00132	0.8
	1	80	0.464	0.1218	0.00276	0.00128	3.8
	1	90	0.473	0.1203	0.00267	0.00126	5.3
Toluene	1	0	0.386	0.1360	0.00376	0.00145	6.6
	1	50	0.421	0.1290	0.00324	0.00136	0.0
	1	80	0.447	0.1248	0.00295	0.00132	3.0
	1	100	0.470	0.1218	0.00276	0.00129	5.3
Bromobenzene	1	0	0.215	0.1410	0.00417	0.00090	0.0
	1	20	0.231	0.1380	0.00390	0.00090	0.0
Chlorobenzene	1	0	0.273	0.1384	0.00393	0.00107	3.6
	1	10	0.298	0.1369	0.00380	0.00113	0.9
	1	20	0.308	0.1357	0.00372	0.00114	1.8
Aniline	1	50	0.503	0.1360	0.00376	0.00189	4.0
	1	100	0.527	0.1298	0.00331	0.00174	4.0
Carbon tetrachloride	1	0	0.198	0.1335	0.00355	0.00070	4.5
	1	20	0.199	0.1306	0.00334	0.00067	0.0
	1	30	0.200	0.1288	0.00322	0.00064	2.9

(Continued on page 180)

Table 6.—(Continued)

Compound	Pres. (atm.)	Temp. (°C.)	C	ω	$\omega^{2.8}$	$C_\omega{}^{2.8}$	% Deviation from Mean
Chloroform	1	0	0.232	0.1318	0.00344	0.00080	5.3
	1	15	0.226	0.1295	0.00327	0.00074	2.6
	1	20	0.234	0.1288	0.00322	0.00075	1.3
	1	30	0.234	0.1273	0.00313	0.00073	4.0
n—Heptane	1	20	0.491	0.1292	0.00324	0.00159	0.9
	1	30	0.519	0.1276	0.00314	0.00162	0.9
n—Butyric acid	1	0	0.444	0.1383	0.00393	0.00175	5.4
		40	0.501	0.1378	0.00389	0.00195	5.4
Acetone	1	0	0.511	0.1293	0.00324	0.00165	1.9
	1	20	0.519	0.1263	0.00305	0.00159	1.9
Ether	1	−50	0.515	0.1298	0.00329	0.00170	21.4
	1	−5	0.525	0.1204	0.00267	0.00140	0.0
	1	0	0.521	0.1190	0.00257	0.00134	4.3
	1	30	0.545	0.1117	0.00214	0.00116	17.1
Butane	1	0	0.551	0.1205	0.00268	0.00148	17.5
	34	37.7	0.595	0.1126	0.00221	0.00132	4.8
	34	93.3	0.650	0.0981	0.00151	0.00098	22.2

THE SEPARATION OF GASES
by Means of Porous Membranes

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Part I. Flow of Gases Through Porous Membranes

Our present knowledge indicates that the separation of mixtures of gases, and of vapors, by means of porous membranes is dependent primarily upon the permeabilities of the individual components of the mixtures. Consequently, the flow phenomena through porous membranes are of basic importance. This investigation was undertaken to elucidate the flow mechanism and the interrelations of mechanisms which are exhibited by different systems of gaseous mixtures.

Theory and Literature Survey

Since Graham's initial investigation in 1829 (*15*), considerable work has been done on the theory of flow of gases through porous media. Various types of flow have been studied and are discussed by Barrer (*5*). These types of flow are (1) molecular effusion; (2) molecular streaming or Knudsen flow; (3) streamline flow or Poiseuille flow; (4) turbulent flow, and (5) orifice flow.

Molecular effusion is flow through a hole of negligible length, and molecular streaming, or Knudsen flow, is flow through a tube of considerable length. In both cases, the diameter of the tube must be small compared with the mean free path of the gas molecules. The difference between the two is that the gas molecules collide with the walls in flowing through the tube, while such collisions are essentially nonexistent in molecular effusion.

Poiseuille, turbulent, and orifice flow are the more common types, when the diameter of the duct is large compared with the mean free path.

Knudsen flow, or molecular streaming, sometimes referred to as molecular flow, was investigated by Graham (*15*). For this type, Maxwell (*26*) showed that the difference in rates of flow of gases depended upon the fact that the relative frequency with which molecules of various components enter the small pore is dependent upon the frequency with which they strike the surface. The more frequently they strike the surface, the greater the probability of their entering a hole. This frequency is directly proportional to their molecular velocities, which are inversely proportional to the square roots of their molecular weights, since each component must have the same average kinetic energy.

Knudsen (*24*) showed that the rate of flow of gas or vapor under these conditions could be expressed as follows:

$$\frac{dn}{dt} = \frac{1}{2} B \frac{1}{\sqrt{2\pi MRT}} \cdot (P - p) \cdot \frac{1}{L} \cdot \left(\frac{2-f}{f}\right) \qquad (1)$$

For circular tubes, $B = 16/3\ r^3\pi$, where r is the radius. This equation may be simplified to

$$dn/dt = \frac{b(P-p)}{\sqrt{M}} \qquad (2)$$

where b is a constant.

In the case of Poiseuille flow of com-

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pressible fluids, the rate of flow may be expressed by

$$dn/dt = \frac{\pi d^4}{128 L\eta} \cdot \frac{1}{RT} \cdot P'(P - p) \qquad (3)$$

This may be reduced to

$$dn/dt = \frac{aP'(P - p)}{\eta} \qquad (4)$$

It is apparent that the main distinguishing points between molecular flow and streamline flow are: molecular flow is dependent only upon the molecular weight and pressure drop; streamline flow upon the average pressure, viscosity and the pressure drop.

Since the nature of fluid flow, in general, depends upon the relation between the diameter of the pores and the mean free path, the nature of the flow changes with the pressure because an increase in pressure decreases the mean free path. In view of this fact, there are three flow regions in flow through membranes—viscous, intermediate and molecular. The intermediate region is a combination of Knudsen and Poiseuille flow. For a given diameter tube, the flow type will change from viscous to intermediate to molecular as the pressure is decreased to zero.

Porous materials have a wide range of pore sizes so that in some of the smallest pores the flow will be of the molecular type, while in the larger pores the flow will be streamline, and in the medium-size pores the flow is intermediate.

Adzumi (*1-4*) combined the equations for streamline and molecular flow for the general case of mixed pore sizes to give the equation

$$dn/dt = \frac{\pi P' N_o r'^4 (P - p)}{8\eta RTL} + \gamma_s \frac{4}{3} \frac{\sqrt{2\pi}}{\sqrt{MRT}} \cdot \frac{N_o r'^3}{L} \cdot (P - p) \qquad (5)$$

where N_o is the number of pores and γ_s is the coefficient of slip.

Expressing these equations in terms of flow rate per unit pressure drop,

$$F_p = dn/dt \cdot \frac{1}{\Delta P} = b/\sqrt{M} + \frac{aP'}{\eta} \qquad (6)$$

It is obvious that for most porous materials a plot of F_p against P' would give a straight line with a slope $[a/\eta]$ and intercept $b/\sqrt{M}$.

Knudsen's experiments led him to suggest that the criterion for molecular flow is that the mean free path be at least two and one-half times the diameter of the pore.

Knudsen (*24*) derived an empirical equation covering the three flow ranges,

$$F_p = a_1 P_{\mu b} + a_2 \frac{1 + C_1 P_{\mu b}}{1 + C_2 P_{\mu b}} \qquad (7)$$

where $P_{\mu b}$ is the average pressure in microbars, a_1 is the viscous flow factor, a_2 the molecular flow factor, C_1 is 1.253 (d/λ_1), λ_1 is the mean free path at one microbar, and d is the diameter of the opening in centimeters. The mean free path is defined as the average distance traversed between successive collisions by all molecules present.

For molecular flow, the rate is governed primarily by the effect of the collisions against the walls and not by intermolecular collisions which determine the viscosity.

The Knudsen equations have been tested by himself and Gaede (*14*) and Klose (*23*) on refractories at low pressures and discussions of these flow equations are many (*11, 21, 25, 28-30, 32, 36*).

Investigations by Hodgins, Flood, and Dacey (*16*), Tomlinson and Flood (*31*), Carman (*9, 10*), and Jones (*19*) showed the existence of another phenomenon in flow through porous media. They observed that in the flow of vapors, rates are greater than expected on the basis of molecular weight and the occurrence of "adsorbed flow" is proposed to explain the phenomenon. Rates of flow of vapors through porous materials are higher than expected, presumably because of mobility in an adsorbed layer on the surface of the porous material. In these studies, charcoal and sintered glass were used as porous materials. Ethyl chloride and diethyl ether were used. A discussion of adsorbed flow is presented also by Wheeler (*36*), who describes recent investigations of this phenomenon.

Jones derived the following equations, considering the flow of adsorbed molecules over the surface of the capillaries,

$$Q_a = \frac{4\pi r^2}{l}\left[\frac{2RT}{\pi M}\right]^{1/2} \int_{m_2}^{m_1} f_m dm \qquad (8)$$

where Q_a is the rate of flow in the adsorbed layer, (g.)/(sec.), m_1 and m_2 are the concentrations of adsorbed gas at the ends of the capillary in (g.)/(sq. cm.), r and l are the radius and length of the capillary, respectively, and f_m is the fraction of adsorbed molecules that are mobile. This equation is based on monomolecular adsorption.

Barrer and Grove (*6*) have shown that adsorbed flow would not account for the deviations observed for carbon tetrachloride and ammonia vapor through

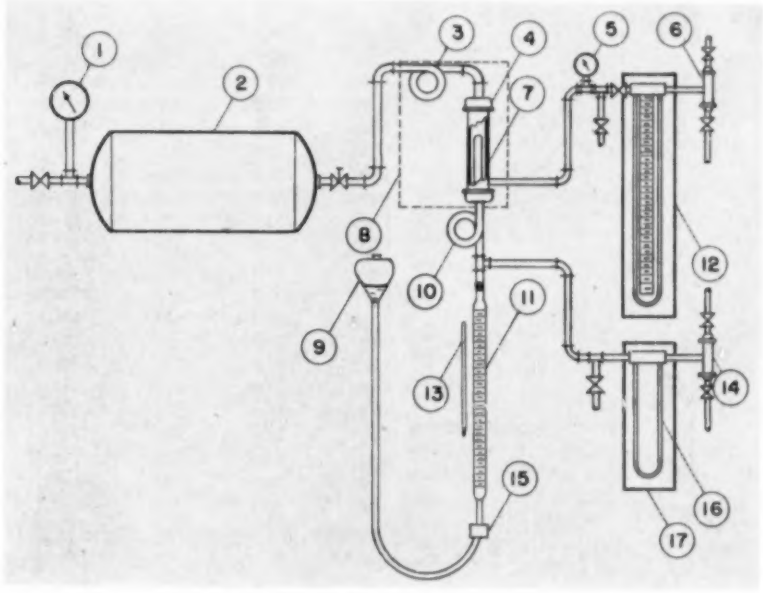

Fig. 1. Porous glass permeability apparatus.

Number	Description	Number	Description
1.	600 lb./sq.in. pressure gauge	10.	Coil for heating or cooling permeated gas
2.	Gas-storage tank	11.	Graduated gas burette
3.	Coil for heating or cooling inlet gas	12.	50-in. Hg manometer
4.	1¼-in. by 8-in. pipe nipple and caps	13.	Thermometer
5.	160 lb./sq.in. pressure gauge	14.	Mercury trap
6.	Mercury trap	15.	Solenoid-operated pinch clamp
7.	Porous glass membrane	16.	Relay contact in manometer leg
8.	Constant-temperature bath	17.	Water manometer
9.	Leveling bulb for burette		

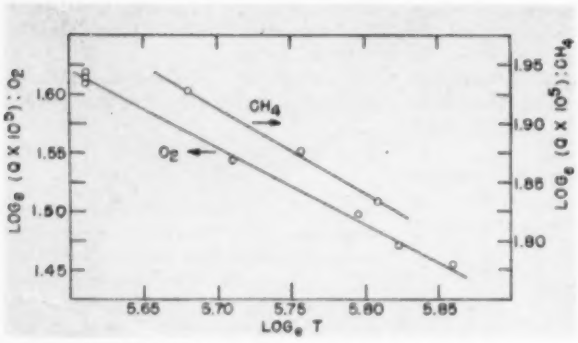

Fig. 2. Plot of log$_e$ permeability vs. log$_e$ temperature.

Table 1.—Gas Permeability Data for Porous Glass

	P', lb./sq.in.abs.	T, ° C.	$Q\sqrt{T}$ † × 10
Nitrogen			
	40.2	14.0	82.2
	40.2	24.1	83.4
	40.2	35.0	84.9
	18.7	24.0	86.5
	52.8	24.0	84.1
	77.2	24.0	83.6
Hydrogen			
	17.3	19.8	292.5
	18.4	25.5	293.5
	33.7	21.0	290.0
	50.2	21.0	291.5
Helium			
	23.7	24.0	214.0
	48.7	24.0	214.0
	74.7	24.0	215.5
Argon			
	23.7	24.0	71.2
	47.2	24.0	71.5
	74.7	24.0	72.2
	77.7	24.0	71.5
Oxygen			
	26.75	0.4	83.0
	26.75	77.1	80.1
	26.75	0.3	82.5
	26.75	28.4	81.3
	26.75	55.7	81.0
	26.75	64.9	80.0
	26.75	0.3	82.9
Methane (99%)			
	26.6	60.0	113.8
	26.75	40.1	115.3
	26.75	20.0	117.4
	19.4	20.0	117.9
	44.2	20.0	117.6
	64.0	20.0	117.8

† Q = (std. cc.)/(sec.)(sq.cm.)(cm. Hg)
T = Temperature, ° K.

Table 2.—Vapor Permeability Data for Porous Glass

	P', atm.	T, ° C.	P'/P$_o$	$Q\sqrt{T}$ † × 10
Carbon Dioxide				
	1.82	28.0	.026	88.7
	1.82	68.6	.013	79.6
	1.82	26.8	.0262	90.5
	1.82	0.7	.0513	102.2
	1.82	0.3	.052	102.4
	1.82	96.3	0091	77.9
	1.82	9.4	.0414	100.9
	1.82	49.9	.0168	86.5
Ethylene				
	1.763	80.0	.01081	105.7
	1.763	55.0	.01545	113.2
	1.763	31.0	.0232	122.7
	2.67	31.0	.0352	122.9
	1.348	31.0	.01774	124.5
Propane (C.P.)				
	1.810	80.0	.0584	90.1
	1.812	65.0	.0778	97.0
	1.822	55.1	.0980	102.0
	1.822	45.3	.1213	108.3
	1.795	95.0	.0446	86.3
	1.813	25.0	.1874	125.6
	1.818	10.0	.280	153.8
	1.816	5.0	.320	167.3
	1.802	0.2	.373	187.0
	2.345	0.2	.487	254.0
	2.685	0.2	.557	471.0
	2.82	0.2	.584	504.0
Butane (C.P.)				
	1.372	79.6	.1386	92.1
	1.204	79.9	.1192	88.6
	1.185	75.0	.1297	93.8
	1.197	70.0	.1475	99.5
	1.276	65.0	.1781	108.9
	1.276	55.0	.228	121.3
	1.199	45.0	.274	143.9
	1.290	35.0	.385	179.6
	1.283	30.0	.450	214.5
	1.293	25.0	.528	293.5
	1.447	25.0	.590	509.0
	1.476	25.0	.602	566.0
	1.522	25.0	.622	671.0
	1.553	25.0	.633	750.0
	1.331	22.0	.589	498.0
	1.388	22.0	.614	699.0
	1.450	22.0	.641	859.0
	1.501	22.0	.664	939.0
	1.533	22.0	.678	985.0
	1.559	22.0	.690	1025.0
	1.586	22.0	.702	1022.0

† Q = (std. cc.)/(sec.)(sq.cm.)(cm. Hg)
T = Temperature, ° K.

analcite crystals at low pressure.

Apparatus and Procedure for Determining Permeability

Porous glass was chosen as the membrane for study because its extremely small pore size permits the investigation of molecular flow and the separation of gases in pressure regions heretofore unexplored.

Porous glass (*18*) is an intermediate in the manufacture of Corning's Vycor glass. It has a fine pore structure, with a mean pore diameter reported to be about 40×10^{-8} cm. (*12, 13*). This diameter is smaller than the mean free path (about 10^{-6} cm.) of most gases at atmospheric pressure and temperature.

A diagram of the equipment is shown in Figure 1.

The porous glass, sealed into a pipe cap with litharge and glycerin and rubber cement, was inserted into a 1¼-in. by 8-in. pipe nipple, with a pipe cap on the other end. Provision was made for gas inlet and outlet on the pipe caps, and also on the side at one end of the nipple. In an alternate assembly, the porous glass was sealed into a rubber stopper with rubber cement which in turn was inserted into the pipe cap and nipple. The former method was found to be more satisfactory. The outside area of the membrane was 44.63 sq.cm., and the thickness was 1.2 ± .01 mm.

The permeability of the porous glass was determined by observing the time required for a definite volume of gas to pass through the porous glass cell for a measured pressure difference. The gas which passed through the membrane was collected at atmospheric pressure and temperature in a graduated gas burette. The pressure difference was measured with either a 50-in. Hg manometer or a Bourdon-type pressure gage. The gas collected in the burette was

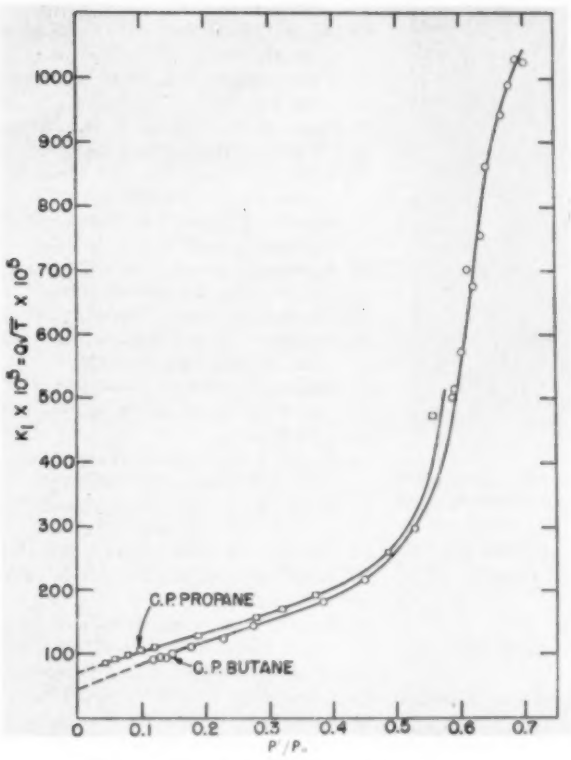

Fig. 3. Permeability data for propane and butane.

Table 3.—Summary of Permeability Data

	T_{cr} (° K.)	Mole Wt.	$Q\sqrt{T} \times 10^5$	$Q\sqrt{TM} \times 10^5$
Hydrogen	33.2	2	292.	413.
Helium	5.2	4	214.	428.
Methane (99%)	191.1	16	117.7	470.
Nitrogen	126.0	28	84.0	444.
Ethylene (C.P.)	282.9	28	88.*	465.
Oxygen	154.3	32	82.2	465.
Argon	151.0	40	71.5	452.
Carbon Dioxide	304.1	44	71.*	471.
Propane (C.P.)	369.0	44	73.*	484.
***n*-Butane (C.P.)**	426.0	58	48.*	366.

* Extrapolated values.

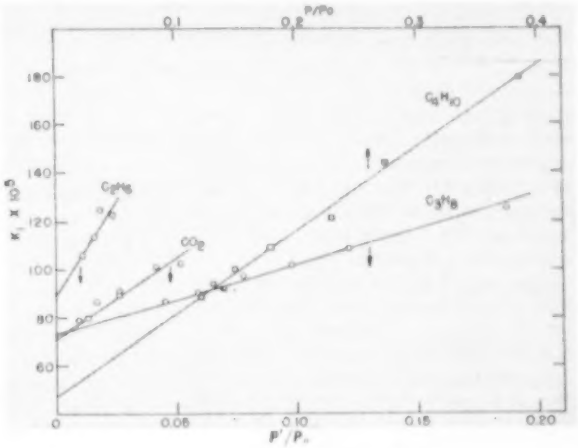

Fig. 4. Extrapolation of permeabilities.

maintained at atmospheric pressure by allowing the displaced fluid to flow from the burette at the same rate as the gas entering. A stop watch timed a definite volume of gas (usually from 10 to 200 cc.). The pressure on the upstream side of the porous glass membrane was maintained constant by a pressure regulator valve.

The cell assembly was either immersed in a constant-temperature bath, or the entire apparatus was placed in a constant-temperature room. When the cell was placed in the constant-temperature bath, a coil of copper tubing was provided so that the entering gas would reach the bath temperature before entering the cell. A similar coil was placed at the outlet, to allow the gas entering the burette to come to atmospheric temperature before the measuring burette.

A saturated solution of sodium chloride was the displacement fluid in the burette to minimize absorption of the gas.

Comment

In order to compare permeabilities taken at different temperatures, the term K_1, called "permeability constant," is defined as equal to $Q\sqrt{T}$. From Equation (1) it can be seen that K_1 should be independent of absolute temperature, T, for any one gas. Figure 2 shows that for oxygen, $K_1 = Q(T)^{.525}$, since the plot of ln Q vs. ln T gives a line with slope equal to -0.525. In the same figure, data for methane give a slope of -0.573. This compares well with the theoretical value of $-.50$ for Knudsen flow. It may be possible that the physical properties of the membrane itself are affected sufficiently by the temperature to account for the deviation from the theoretical behavior.

The permeabilities of hydrogen, helium, methane, oxygen, argon, and nitrogen were found to be independent of average pressure over the pressure range investigated (Table 1). This fact indicated that the flow was predominantly molecular, or Knudsen, in type and thus Equations (1) or (2) should describe the flow.

The permeabilities of propane and butane, however, were found to vary with average pressure and temperature as shown in Table 2. It is apparent that some phenomenon other than molecular flow is taking place. These data could be correlated by plotting K_1 against the ratio, P''/P_o, that is, average pressure, P'', to vapor pressure P_o, as shown in Figure 3. It appears that the increase in permeability with increasing pressure, or decreasing temperature, might be the result of flow in a mobile adsorbed layer. If it seems logical that the magnitude of the adsorbed flow would increase with an increasing amount of vapor adsorbed, extrapolation of the data of Figure 3 to a lower pressure, or a higher temperature, should give values of permeability constants in which adsorbed flow does not contribute. The intercept of these curves at $P''/P_o = 0$ would yield the "true" molecular flow permeability constant K_1, since there should be no adsorption at $P''/P_o = 0$.

Permeabilities of carbon dioxide and ethylene were plotted against P''/P_o in a similar manner. Variations in the case of carbon dioxide and ethylene were obtained by varying the temperature, and hence P_o. It was found that K_1 was practically independent of average pressure of CO_2 and C_2H_4. In this respect they differ from propane and butane. The range of the P''/P_o ratio is much less in the case of these more gaslike substances. As might be expected, the phenomenon of adsorbed flow is observed at conditions near or below the critical temperature of the substance being studied, when the substance begins to behave more as a vapor.

The extrapolated values of K_1 for propane, butane, carbon dioxide and ethylene were obtained from Figure 4. The permeabilities, K_1, for all of the gases, and the extrapolated values for the vapors are plotted against their respective molecular weights on a log-log scale in Figure 5. These points all lie on a straight line with the exception of butane, which is quite low. The remainder are within the range of experimental accuracy. It should be noted that the

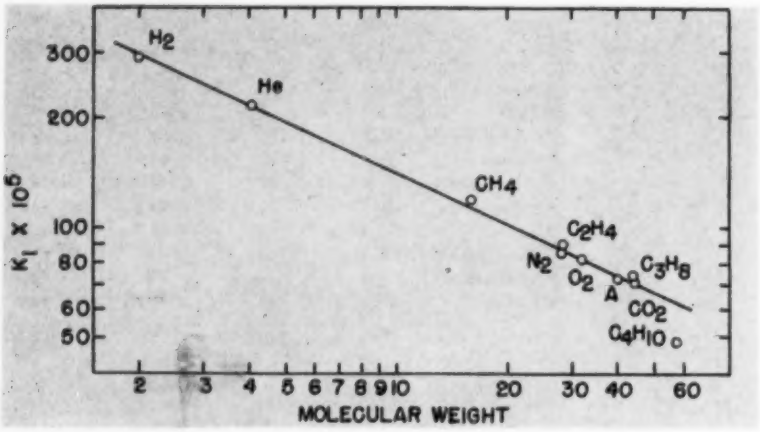

Fig. 5. Log permeability vs. log molecular weight.

slope of this line is −0.465 compared with the theoretical value of −0.50. This deviation from theory is due probably to experimental errors, and may account for some of the deviations of calculated values in Part II of the paper (see Table 3-a summary of permeability data).

The low value of extrapolated permeability for butane cannot be explained on the basis of adsorbed flow. It is possible that the size of the relatively large butane molecule may account for the low permeability. Some of the smaller pores may be blocked, or made ineffective, by the large butane molecule.

Some preliminary evidence indicated that the permeability of butane and propane reached a maximum value and decreased sharply at high P''/P_o ratios. Permeabilities, determined when the ratio of upstream pressure to vapor pressure was greater than 1.0, were lower than all other values, but because of an unstable condition, no definite value of permeability was obtained.

A great uncertainty was involved in the determination of the vapor permeabilities because of the problem of equilibrium. The attainment of the steady state of flow often took a rather long time. The flow rate was sensitive to extraneous adsorbed materials, such as moisture or the previous gas tested.

Jones (*19*) equation for mobility of a monomolecular layer would not be expected to apply in this case since it has been shown (*8*) that adsorption of butane on porous glass is of the multimolecular, or multilayer, type.

Notation

a = a constant
b = a constant
B = a constant
d = diameter of pore or duct
f = fraction of molecules striking wall and emitted with random velocity distribution
F_p = flow rate per unit pressure drop
F = fraction of feed gas permeating membrane
K_1 = permeability constant ($Q\sqrt{T}$)
K_2 = membrane constant ($Q\sqrt{TM}$)
L = length of pore
M = molecular weight
N = gas flow rate, (std.cc.)/(min.), or (moles)/(unit time)
p = absolute pressure on downstream side of membrane
P = absolute pressure on upstream side of membrane
P' = average pressure = $(P + p)/2$
P_o = vapor pressure
ΔP = pressure drop across membrane
Q = corrected gas permeability, (std.cc.)/(sec.)(sq.cm.)(cm.HgΔP)
r = radius of pore
r' = average radius
R = gas constant
S = area of membrane, sq.cm.
T = absolute temperature
x = mole fraction of component in gas mixture on upstream side of membrane
y = mole fraction of component in gas mixture on downstream side of membrane

Subscripts and Superscripts

A = component designation
B = component designation
f = feed gas
o = unpermeated, or high pressure outlet gas
p = permeated gas

Greek Letters

α = Q_1/Q_2, or $\sqrt{M_2/M_1}$, ratio of permeabilities
β = N_p/Q_1S
γ_s = coefficient of slip
γ = N_o/N_p
η = viscosity

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Part II will be run in an early issue.

Drop-Size Distributions From Spray Nozzles

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The performance of spray nozzles is of technical interest because of varied industrial applications, especially spray drying. In spite of the sometimes high value of materials handled and the high cost of some type of spray equipment, exact design procedures are not, in general, available. Consequently, a considerable amount of uncertainty is involved in the design and construction of such equipment, and occasionally it proves impossible to produce specified results from the apparatus under any circumstances.

This uncertainty in design is due to a number of factors which are incompletely known, such as the air-flow patterns in the apparatus, the droplet velocities and trajectories, and mass- and heat-transfer rates at the droplet surfaces. One of the difficulties is the lack of knowledge of the droplet-size distributions produced by various types of nozzles. The purpose of this work was to obtain some information on droplet-size distributions produced by certain pressure nozzles. The investigation was concerned with the size distribution of the droplets produced by a few commercial nozzles, rather than with the factors of nozzle design which ultimately control the action of the nozzles, and the problem is treated from an empirical, rather than a theoretical approach.

Although the use of spray nozzles to subdivide liquids into droplets is widespread, the process involved is not well understood. The limited amount of drop-size data in the literature is not accompanied by an entirely satisfactory correlation, even on an empirical level; and there is no complete theoretical treatment.

The manner of breakup of liquid into droplets has been qualitatively discussed by Castleman (*1*) for air atomizers, and by Fogler and Kleinschmidt (*5*) for pressure nozzles. The large number of variables involved has prevented any great utility of dimensional analysis. Empirically, Nukiyama and Tanasawa (*12*) developed dimensional equations to represent their results with small air-atomizing nozzles. Lewis, et al. (*9*), suggested the applicability of the equations to data for pressure nozzles, although the size-frequency equation leaves much to be desired. Others, Joyce (*8*), Longwell (*10*) have applied the Rosin-Rammler equation (*13*) to spray size-frequency data.

In the present work, preliminary size-frequency data indicated that the above-mentioned methods of representation were not wholly satisfactory. The Nukiyama-Tanasawa distribution equation

$$\frac{dn}{dx} = ax^2e^{-bx^2} \qquad (1)$$

graduated the measured frequencies adequately where they were not zero, but above the largest observed sizes, the calculated number-frequency curves were distressingly high. This equation often gives surface-mean droplet diameters larger than any of the observed droplets, as noted by Lewis, et al. although, on the average, one expects the surface-mean diameter to be less even than the mass- or volume-mean. The equation does have the advantage that the range of sizes in any spray from a given nozzle is described by one constant, q. The Rosin-Rammler equation

$$R = e^{-0.693(x/x')^N} \qquad (2)$$

gives a better fit to the data, although it still has a noticeable "tail" above the largest sizes observed. One would expect to find some maximum-size limit in a spray cloud. In this equation the exponent N describing range is not independent of mean-droplet diameter for a given nozzle. Both of these methods use graphical determination of the constants of the equations. The resultant simplicity is outweighed by the fact that in both cases the method of plotting tends to obscure instead of minimize deviations from the assumed function.

In an effort to find a more appropriate size-frequency function, several standard curve-fitting methods were tried, among them Pearsons' curves (*2*) and several series based on the probability function. None of these methods fits the data satisfactorily. Finally, an empirical modification of the logarithmic-probability function was developed to fit the experimental data.

Experimental

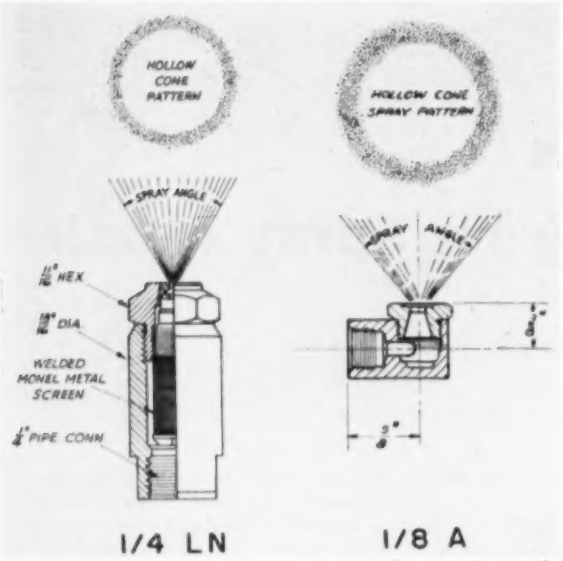
The work here reported involved spraying into air liquid organic materials fusing well above room temperature. The sprayed material was allowed to freeze before falling onto the collecting surface. The sprayed droplets were thus preserved for measurement regardless of later handling. The collected sprayed powder was sampled for microscopic-size determination, avoiding sampling errors due to nonuniformity of the spray pattern.

Two designs of nozzles were used, both hollow-cone pressure nozzles, in which the liquid enters tangentially a whirl chamber behind the orifice, from which it leaves as a hollow sheet (Fig. 1). The sheet moves out in the form of a hollow cone, as it breaks up into droplets a short distance from the orifice. The nozzle parts are of the same size in different capacity models of the same design. Thus for neither design is there complete geometric similarity among nozzles of different capacities. The nozzles used were made by Spraying Systems Co.

Materials sprayed were beta naphthol and benzoic acid, which were distilled between runs to maintain purity. A few other organic materials were tried but found unsuitable for various reasons.

Supplementary data (including complete Table 3) are on file (Document 3913) with American Documentation Institute Auxiliary Publications, Photoduplication Service, Library of Congress, Washington 25, D. C. Obtainable by remitting $1.75 for microfilm or $2.50 for photoprints.

G. M. Turner is currently associated with Du Pont Co., Wilmington, Del.



Courtesy, Spraying Systems Co.

Fig. 1. Nozzle designs.

TABLE 1.—PHYSICAL PROPERTIES OF SPRAY LIQUIDS

Temp. °C.	Viscosity centipoise	Temp. °C.	Density g./cc.	Temp. °C.	Surface Tension dynes/cm.
		Beta-Naphthol			
183.0	0.939	181.0	1.0362	183.3	32.4
159.6	1.27	158.6	1.0528	157.3	34.6
130.2	2.03	132.0	1.0733	131.3	37.2
		Benzoic Acid			
182.9	0.746	187.4	1.024	183.4	26.0
157.2	0.963	153.0	1.055	157.3	28.2
131.3	1.292	133.6	1.073	131.5	30.8

Since the literature affords limited data on the physical properties of these materials as liquids above their melting points, the density, viscosity and surface tension were determined (Table 1). The necessary temperatures were obtained in an oil bath. Densities were determined from the loss in weight of a Pyrex glass shot-weighted bob, whose volume was determined by loss of weight in water at room temperature and corrected for thermal expansion of the glass. Viscosities were determined by means of a Pyrex glass Ostwald viscosimeter calibrated when containing 5 ml. of water at 20° C. The material was added to the viscosimeter as a powder in weighed amounts to give 5 ml. at the desired temperature. Corrections for the thermal expansion of the glass were calculated and found to be negligible with respect to timing errors. Surface tensions were determined by the ring method. The measured dimensions of the ring and the Harkins and Jordan (6) tables were used to calculate the surface tensions from the measured force maxima.

The spray material was melted in a pot made from a piece of 3-in. steel pipe 5 in. long, closed by steel end plates. The nozzle was mounted at the center of the welded bottom plate, while pressure for spraying was applied through a flexible connection to a gas cylinder. In the later runs a welded liner of 16-gauge stainless steel was inserted to avoid attack by molten benzoic acid.

The electric heaters used were manually controlled by adjustable autotransformers. The temperature was measured by means of iron-constantan thermocouples; the indication of a thermocouple in the liquid line close to the nozzle was taken as the spray temperature.

To avoid the necessity of a liquid-line valve, the pot was mounted on pivots. Just before spraying, a weight pulled the pot around against a stop placing the nozzle in spraying position. At other times the nozzle was above the liquid level.

The spray pot was mounted at the top of a space 4 ft. square by 10 ft. high, enclosed so that the spray powder could not drift away. Eight inches below the spray position of the nozzle the sprayed material was intercepted by a tray unless it was pulled out of the way.

The procedure in making a run was as follows:

The pot was filled with the (solid) material to be sprayed and placed in the pivots with the nozzle in the horizontal position. When the material had been heated to the desired temperature, the pot was tipped down to the spray position and spraying started by admitting carbon dioxide under a predetermined pressure into the pot. As soon as the pressure gauge was steady, the tray was pulled out of the way, and a stopwatch was started. At the end of the desired period, the tray was returned under the nozzle and the watch was stopped. At once, the valve from the pressure regulator was closed, and a cock was opened to release the gas pressure in the spray pot. The pot was then tipped up to prevent further drip from the nozzle onto the tray.

After a lapse of a few minutes to allow settling of the finest material, the paper sides of the chamber were tapped to knock down any dust that had settled on them. Papers on the floor of the chamber were then picked up, and the powder carefully shaken and brushed into a beaker for weighing and sampling. The flow rate was determined from the weight of material collected and the length of the spray period.

For sampling, the weighed spray material was dumped onto a sheet of aluminum foil, and gently but thoroughly mixed by means of a spatula. The pile was then split repeatedly, until the original sample of more than 100 g. was reduced to about 1 g., which was then suspended in about 50 ml. of mineral oil.

While this suspension was stirred violently, a few drops were withdrawn and placed on a square cover glass rimmed with Vaseline. After a few minutes settling time, a slide was placed on the cover glass and turned over. The slide was examined by vertical projection onto a 3¼- by 4¼-in. ground glass in a microscope camera. A transparent rule was used to measure the images, which were counted in groups corresponding to steps of 20μ or 10μ in particle diameter. Fields were counted according to a checkerboard pattern covering the entire area inside the Vaseline rim. Particles were generally measured in about ninety fields per slide, although the more frequent smaller particles were counted in only twenty-five of these fields. From one to three slides per run were counted, the usual number of particles counted being about 1000, with the adjusted total being roughly 2000 for a run.

Empirical Size-Frequency Function

Inasmuch as spray size-distribution data usually can be considerably straightened by plotting on logarithmic vs. cumulative probability coordinates, an empirical method based on the logarithmic probability function was developed. Use of this function has a quasi-theoretical basis in that a repeated random process which results each time in growth or diminution by constant factors leads to a logarithmic-probability distribution. Epstein (*3*) has showed numerically how a crushing process can in this way lead to such a distribution.

The procedure used is to calculate the appropriate mean size and standard deviation from the observed frequency data. Ratios of the experimental frequencies to those obtained from the logarithmic normal probability function with the same mean and standard deviation are then calculated and used as an empirical-adjustment curve.

The volume frequency vs. size distribution must be used rather than the number-size distribution, since unavoidable errors in collecting and measuring the numerous smallest droplets make the number frequency more subject to error. Also, the volume frequency is usually of more practical utility.

The characteristic size, x', is defined by

$$\log x' = \frac{\Sigma n x^3 \log x}{\Sigma n x^3} \quad (3)$$

The range of sizes is measured by the logarithmic standard deviation, again on a volume basis:

$$\sigma = \frac{1}{\Sigma n x^3} \sqrt{(\Sigma n x^3)(\Sigma n x^3 \log^2 x) - (\Sigma n x^3 \log x)^2} \quad (4)$$

It was found that, while σ varies somewhat from one run to another, there is little or no trend for a given nozzle. The effect of fluctuations in counting is much greater on σ than on $\log x'$. Thus it is desirable to obtain an improved estimate, σ', by averaging the values obtained in individual runs. The method chosen was to average σ^2, as a variance, weighting the values of σ^2 by the adjusted number of measured particles.

The logarithmic probability function may be written

$$q(z) = \frac{1}{\sqrt{2\pi}} e^{-z^2/2} \quad (5)$$

where z is defined by

$$z = \frac{\log x - \log x'}{\sigma} \quad (6)$$

Inasmuch as the experimental data are obtained in terms of x rather than z, a more useful form of the logarithmic probability function is obtained by setting

$$f(x)dx = q(z)dz \quad (7)$$

where $f(x)$ is the frequency function on an arithmetic scale transformed from the probability function on a logarithmic scale. As a result,

$$f(x) = \frac{1}{2.303\sigma x} q(z) \quad (8)$$

While there are many tabulations of the probability function available, the ones used in this work are the four-place table in the "Handbook of Chemistry and Physics" (*7*), and where more places were needed, the "Mathematical Tables Project" tabulation (*11*).

The departure of the observations from the logarithmic probability function is expressed by introducing into Equation (8) an adjustment factor K

$$f(x) = \frac{K}{2.303\sigma x} q(z) \quad (9)$$

So far, no assumptions have been made about the nature of K. One might expect, however, that K would not depart far from unity for most of the observed size range, and that it would go to zero to express the impossibility of finding drops beyond some maximum-size limit. There is no à priori reason to expect that the deviations from the reference function [Equation (8)] would not change with different spray runs. It turns out, however, that the curve of K against z is, for any one of the nozzles examined, practically independent of the particular conditions of a spray run. The differences among the curves for individual runs with a given nozzle appear to be random. These differences are decreased if the K's are obtained from the experimental data by use of σ' for the nozzle in calculating the size variable z and in Equation (9). For this purpose, $f(x)$ in Equation (9) is replaced by the observed volume frequency $nx^3/\Sigma nx^3$. The K vs. z data, so obtained for each nozzle, were grouped and an average curve for the

TABLE 2.—SPRAY RUN DATA

Run number	Material sprayed	Temp. °C.	Press. lb./sq.in.	Flow rate gal./sec.	Viscosity centipoise	Density g./cc.	Surface tension dynes/cm.	$\bar{x}$ microns	σ
Nozzle ¼: Orifice diameter = 723 μ									
1	BA	143	34	1.84	1.13	1.063	30.1	98	.164
2	BA	146	59	2.36	1.09	1.061	29.5	79	.086
3	BA	142	127	3.36	1.14	1.064	30.0	74	.159
4	BN	133	32½	2.00	1.93	1.073	36.9	116	.193
5	BN	134	51	2.45	1.90	1.072	36.8	103	.190
6	BN	134	88	3.07	1.90	1.072	36.8	95	.105
								Mean	.1488
Nozzle ¼: Orifice diameter = 1092 μ									
7	BN	135	34	3.46	1.86	1.071	36.8	155	.190
8	BN	132	44	4.59	1.96	1.073	37.0	138	.180
9	BN	131	62	5.57	1.98	1.074	37.2	125	(.199)
10	BN	134	89	6.36	1.89	1.072	36.8	111	.184
11	BN	177	26	3.26	1.06	1.040	32.8	152	.178
12	BN	182	33	3.68	0.94	1.036	32.4	134	.217
13	BN	180	46	4.34	0.97	1.038	32.6	116	.201
14	BN	180	63	4.99	0.97	1.038	32.6	108	.204
15	BN	180	85	5.66	0.97	1.038	32.6	104	.183
								Mean	.1906
Nozzle ¼: Orifice diameter = 1076 μ									
16	BN	134	34	3.83	1.89	1.072	36.8	158	.180
17	BN	137	45½	4.30	1.80	1.070	36.6	136	.176
18	BN	131	63	5.03	1.98	1.074	37.2	117	.177
19	BN	131	89	5.99	1.98	1.074	37.2	106	.182
20	BN	182	27	3.03	0.94	1.036	32.4	137	.151
21	BN	182	43	3.59	0.94	1.036	32.4	120	.175
22	BN	180	84	4.98	0.96	1.038	32.6	104	.168
23	BA	170	27	2.99	0.84	1.040	27.3	116	.165
24	BA	170	37	3.43	0.84	1.040	27.3	116	.159
25	BA	170	63	4.64	0.84	1.040	27.3	87	.162
26	BA	168	89	5.47	0.86	1.042	27.5	85	.167
27	BA	166	126	6.67	0.90	1.043	27.7	84	.178
28	BA	142	35	3.57	1.14	1.065	30.0	112	.154
29	BA	139	46	4.09	1.18	1.069	30.2	108	.174
30	BA	134	127	7.02	1.25	1.072	30.7	81	.173
								Mean	.1720
Nozzle ¼: Orifice diameter = 1521 μ									
31	BA	144	32	8.05	1.17	1.063	29.7	149	.176
32	BA	148	62	11.2	1.07	1.059	29.3	135	.204
33	BA	146	122	15.9	1.12	1.061	29.5	115	.193
34	BN	135	34½	8.60	1.86	1.071	36.8	186	.194
35	BN	136	60	11.8	1.83	1.070	36.7	152	.204
36	BN	135	122	17.2	1.86	1.071	36.8	142	.211
								Mean	.1990

BN = Beta Naphthol
BA = Benzoic Acid

(Continued on page 188)

nozzle calculated. For high negative values of z where the value of K changes markedly within each block, the geometric mean K's were calculated. Elsewhere the arithmetic average K was used. Inasmuch as the averaged K vs. z curves for the individual nozzles were similar in form and showed small quantitative differences, these average curves were combined, and equations determined, derived to express the over-all average. These equations are

$$K = 1.048 + 0.253z - 0.0620z^2 - 0.0824z^3 \cdot (-2.0 \leq z \leq 2.5)\ K = 0(z \geq 2.5) \quad (10)$$

and

$$\log K = -1.362 - 0.671z(z \leq -2.0) \quad (11)$$

Equations (10) and (11) are plotted as Figure 2. While these values have not been adjusted to bring the area under the resulting size-frequency curve to unity, the integral is within one per cent of unity (1.0074). Equation (10) is derived by the method of least squares, which indicates a r.m.s. error of .15 in K, although in the region of large frequencies the fit is actually better. K goes to zero at a value of z which is a little high, and it is here that the largest errors in K enter. The practical effect of this error is slight. Equation (11) is obtained graphically.

The form of size-frequency curve obtained is shown in Figures 3 and 4, in which the experimental data are plotted as volume frequency histograms. The smooth curves are obtained from Equations (9)-(11), using in each case the mean size derived from the data for the run and the average standard deviation for the nozzle. The small bump in the curves in the region of small sizes is due to the change of equations, and is not inherent in the data. Typical measured size distributions are presented in Table 3.

Table 2.—(*Continued*)

Run number	Material sprayed	Temp. °C.	Press. lb./sq.in.	Flow rate gal./sec.	Viscosity centipoise	Density g./cc.	Surface tension dynes/cm.	$\bar{X}$ microns	σ
			Nozzle ⅛: Orifice diameter = 1440 μ						
37	BN	136	33	10.5	1.86	1.070	36.7	180	.198
38	BN	135	47	12.4	1.86	1.070	36.8	176	.196
39	BN	142	89	17.0	1.67	1.066	36.1	154	.199
40	BN	130	125	20.8	2.02	1.075	37.2	143	.186
41	BN	180	34½	9.72	0.97	1.038	32.6	156	.191
42	BN	182	44	10.9	0.95	1.036	32.4	144	.194
43	BN	180	63	12.6	0.97	1.038	32.6	144	.195
44	BN	182	89	14.4	0.94	1.036	32.4	138	.194
								Mean	.1936
			Nozzle ⅛: Orifice diameter = 1460 μ						
45	BN	133	34	11.4	1.92	1.072	37.0	214	.192
46	BN	130	37½	12.0	2.02	1.075	37.2	207	.201
47	BN	130	45	13.2	2.02	1.075	37.2	189	.205
48	BN	134	55	14.4	1.90	1.072	36.8	182	.194
49	BN	134	62	15.2	1.90	1.072	36.8	173	.204
50	BN	130	88½	18.3	2.02	1.075	37.2	166	.206
51	BN	136	117	20.4	1.82	1.070	36.7	141	.201
52	BN	184½	34½	10.0	0.90	1.034	32.2	173	.169
53	BN	181	42½	11.1	0.96	1.037	32.5	162	.186
54	BN	179	62	13.6	0.98	1.038	32.7	145	.191
55	BN	182	89	15.6	0.94	1.036	32.4	134	.195
56	BA	174	33	9.12	0.81	1.037	26.9	148	.172
57	BA	136½	33	10.2	1.22	1.069	30.4	165	.174
58	BA	146	45	11.7	1.09	1.060	29.5	154	.188
59	BA	142	61	13.3	1.14	1.064	30.0	145	.200
60	BA	142	123	18.6	1.14	1.064	30.0	119	.191
								Mean	.1930
			Nozzle ⅛: Orifice diameter = 2030 μ						
61	BA	142	34	20.5	1.14	1.064	30.0	203	.206
62	BA	137	43½	23.2	1.21	1.069	30.4	187	.202
63	BA	142	62½	26.9	1.14	1.064	30.0	186	.226
64	BN	130	33	21.9	2.02	1.075	37.2	227	(.239)
65	BN	136	43	24.8	1.82	1.070	36.7	219	.204
66	BN	130	61	27.9	2.02	1.075	37.2	192	.204
								Mean	.2048

Droplet-Size Data Correlation

As was mentioned previously, the factors and relations governing the mean size, x', are so complicated that dimensional reasoning is of little help. Consequently, a completely empirical treatment of the mean sizes was used. Data of the various runs were combined insofar as seemed justifiable, and were fitted to functions of the form

$$x' = CD^n w^b \nu^c \mu^d \quad (13)$$

These functions were fitted to the data by converting to the logarithmic form and using the method of least squares. Each run was weighted equally. Figure 5 is a plot of mean size against flow rate. The run data are tabulated in Table 2.

The following equations were chosen as the best representation of the experimental data for each type of nozzle tested.

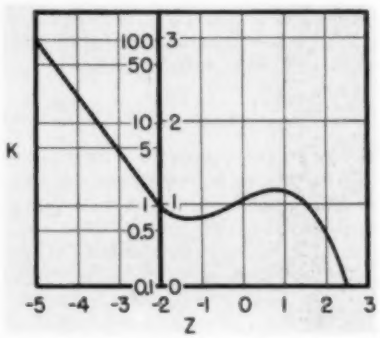


Fig. 2. Adjustment factor, K vs. size variable, Z.

For the four $1/4LN$ nozzles (36 runs),

$$x' = 16.56D^{1.520}w^{-0.444}\nu^{0.713}\mu^{0.159}$$

(mean error—8%) (14)

For the two $1/8.4SS$ nozzles (21 runs),

$$x' = 41.4D^{1.589}w^{-0.537}\nu^{0.594}\mu^{0.220}$$

(mean error—5%) (15)

The small range of densities made introduction of this variable unjustified, as shown by significance tests.

A plot of the $1/8.41(A)$ data as mean diameter x' against flow rate w shows a markedly different slope from that for the other two nozzles of this design. As this was a brass nozzle, only beta naphthol runs could be made; and the resulting variation in physical properties proves to be insufficient to separate the effects of surface tension and viscosity. The only reliable exponent obtained is −0.38 on the flow rate.

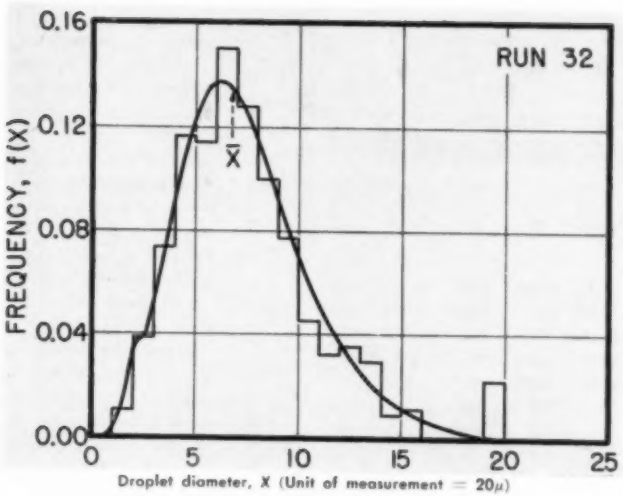


Fig. 3. Size-frequency curve.

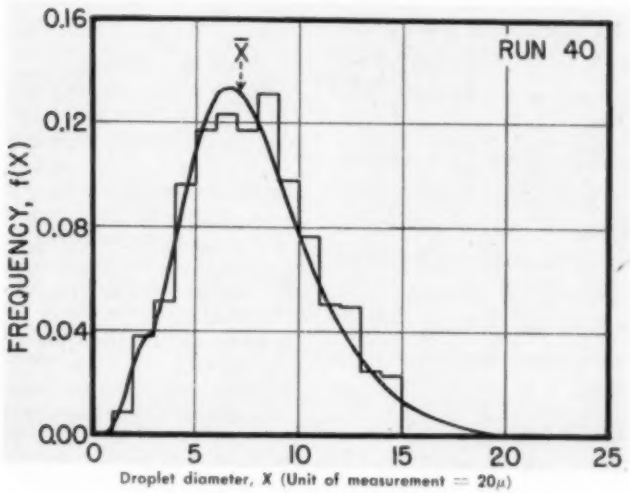
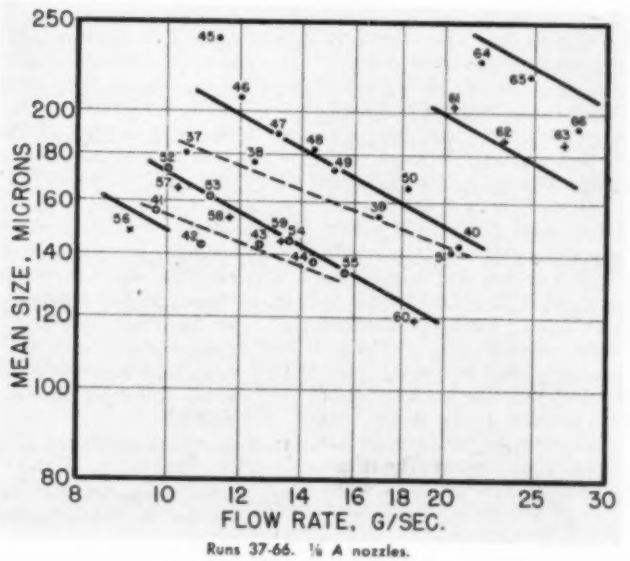


Fig. 4. Size-frequency curve.



Runs 37-66. ⅛ A nozzles.

Fig. 5. Mean size, $\bar{x}$, vs. flow rate, W.

The standard deviations for each nozzle, σ', were correlated with nozzle orifice diameter by the equation

$$\sigma' = 0.173 + 0.126 \log D \qquad (16)$$

with a r.m.s. deviation of 0.0085 or 5% of the mean. The correlations of mean droplet sizes and of standard deviations hold only for the particular nozzles tested, and can be considered only as first approximations for other nozzles, even of identical design.

Errors

There are two main types of error entering into the experimental data. The first category includes the errors due to neglect of some of the processes occurring in the spray, the second includes sampling and measurement errors.

In the correlations of mean drop size vs. spraying conditions, the liquid properties are taken as those of the liquid shortly before it leaves the nozzle. The temperature change during liquid breakup is of the order of several degrees Centigrade. A certain amount of recombination of liquid droplets takes place between the time of breakup and of freezing. The result of the temperature and recombination uncertainties is some uncertainty in the reliability for a particular purpose of the results obtained. This disadvantage is offset by the advantage obtained in the sampling procedure available when the droplets can be sampled as a frozen powder.

There are possible errors in the sampling technique used because of segregation, or incomplete mixing; the care taken, and comparison of different slides for the same spray indicate that these errors are small. Errors in measurement in most cases will result in a particle being recorded in a group adjacent to its proper place; the net effect of all such errors is probably small.

Some additional error in the correlations results from the necessary, but arbitrary, simplicity of the exponential equations. Without a theoretical treatment, no other form is obviously preferable. In view of the lack of geometrical similitude among nozzles, the use of orifice diameter alone to describe the nozzle is also an oversimplification.

Comment

For a few nozzles, the three kinds of information are required to describe the drop sizes produced by a spray nozzle: the form of the distribution curve, a measure of the range of sizes, and the characteristic size for each spray.

It is convenient that the form of the function does not vary importantly, either among runs or among the nozzles tested. It is also convenient that the range (standard deviation) can be taken

TABLE 3.—TYPICAL MEASURED-SIZE DISTRIBUTIONS

Run number	6	10	19	35	39	50	66
$\bar{x}$ microns	95.4	110.6	105.5	151.7	154.3	165.5	192.3
σ	.1053	.1837	.1823	.2045	.1993	.2056	.2039
Group width microns	10	10	10	20	20	20	20
Group							
1	87*	176*	120*	282*	440*	604*	178*
2	527*	523*	700*	720*	767*	1164*	635*
3	380*	665*	588*	462*	586*	692*	384*
4	297*	523*	452*	360*	331*	384*	205*
5	143*	389*	380*	185	262*	407*	232*
6	159	346*	300*	140	152	221	130
7	106	290*	264*	100	121	155	97
8	105	259	227	59	79	116	54
9	69	174	186	40	58	90	44
10	48	134	173	21	29	45	37
11	35	111	121	20	29	28	27
12	17	93	66	12	16	24	25
13	11	57	43	7	5	19	15
14	11	49	33	2	4	6	11
15	2	33	27	2	3	5	8
16	5	24	20	0	1	3	1
17	4	11	9	2	2	2	4
18	2	15	7	0	0	4	4
19	0	9	2			0	2
20		5	5				0
21		4	2				
22		1	2				
23		1	1				
24		1	1				
25		0	0				
Adjusted total	2008	3893	3729	2414	2885	3969	2093

*Adjusted

as a constant for a given nozzle, and for the nozzles used, can be approximated as a function of the orifice diameter. As a result the variations in the entire drop-size distribution can be represented by those of a single quantity, the mean droplet diameter, x'. This simplicity of treatment is achieved without any particularly arbitrary assumptions about the form of the data or the nature of the break-up process. It remains to be proved just how generally these functions can be applied.

An advantage of the size-distribution representation developed here is that Equations (9)-(11) can be used to calculate the coordinates for graph paper similar to logarithmic-probability paper. Drop-size distributions similar to those of this work plot as straight lines on such coordinates, with attendant simplification in the approximation of the mean size and standard deviation. This simplification involves somewhat less violence to the data than straight-line methods mentioned previously. In contrast to ordinary logarithmic-probability coordinates, these plots show a definite maximum size limit.

Some useful general conclusions can be drawn as to the magnitude of the effects of the variables correlated. The mean drop size is proportional to the orifice diameter to approximately the 1.5 power when the flow variable is weight rate; if this be converted to a velocity term (w/D^2), the drop size is proportional to the 0.5-0.6 power of the diameter. This is in accord with the results of Joyce rather than of Longwell. The range of the distributions, expressed as standard deviation, increases with nozzle size and is unaffected by other variables studied. The weight flow rate enters to the minus 0.38 to 0.58 power, in approximate accord with the results of other workers, but emphasizing the great importance of slight differences in manufacture among nominally identical nozzles. The surface tension is of major importance, appearing to powers from six tenths to unity. The viscosity is of less effect, entering as the fourth root or less. No conclusion can be drawn as to the effect of liquid density. The effects of other variables have not been determined.

Notation

a = constant in Equation (1). Also, exponent of D in Equation (13).
b = constant in Equation (1). Also, exponent of w in Equation (13).
c = exponent of ν in Equation (13).
d = exponent of μ in Equation (13).
e = 2.71828.
$f(x)$ = frequency function graduating experimental-size distribution.
n = number of particles counted.
q = exponent in Equation (1).
w = flow rate, g./sec.
x = droplet diameter, units of measurement group width.
x' = mean droplet diameter. Units as above, or for correlation, microns.
z = logarithmic size variable, Equation (6).
C = coefficient in Equation (13).
D = nozzle orifice diameter, mm.
K = adjustment factor, Equation (9).
N = exponent of Rosin-Rammler Equation (2).
R = volume fraction smaller than size x, Equation (2).
σ = logarithmic standard deviation, Equation (4).
σ' = mean σ for nozzle.
$\varphi(z)$ = probability function, Equation (5).
ν = liquid surface tension, dynes/cm.
μ = liquid viscosity, centipoise.

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    [cf. (9)]
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Mass Transfer in Packed Beds at Low Reynolds Number

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This paper presents experimental data for the transfer of mass from solid pellets in packed beds to water flowing at low velocities in the surrounding voids. Solids employed were 2-naphthol and benzoic acid. Two new methods, one colorimetric and the other volumetric, have been developed for measuring low concentrations of 2-napthol. Data extended from Reynolds number (*Re*) values of 10^{-2} to 10^{1}. Together with the data of Gaffney and Drew *(16)* and McCune and Wilhelm *(26)*, a smooth correlation, using the Colburn *j* factor, was obtained for liquids over a Reynolds number range of 10^{-2} to 10^{4}. Below *Re* of 5, the curve for benzoic acid shows high *j* factors for the same *Re* values. This explained in terms of free convection and the Grashof number. Other variables not prevalent in the turbulent region are discussed for the transition and laminar regions. The need for further work in all regions for both liquids and gases is pointed out with specific recommendations.

Mass transfer between a surface and a moving stream of liquid or gas is an important factor in controlling rates in numerous chemical engineering operations, such as absorption, extraction, leaching, drying, adsorption, and ion exchange.

In processes where external mass transfer is the principal rate variable, the effect of velocity of the fluid stream on the rate-transfer coefficient is required for design purposes. A survey of the recent literature in the fields of adsorption and ion exchange showed that considerable discrepancy exists in the effect of velocity on the over-all rate constant. Table 1 summarizes these findings. Where there is no dependence on velocity, it might be assumed that internal pore diffusion or slow chemical reaction is controlling. For the other examples cited, the fluid-film resistance was predominant and the rate constant varied with a power of the mass velocity which ranges from 0.23 to 1.0. In some cases, the modified Reynolds number range was the same, but the exponents given by the investigators were different. The exponent, *n*, of 0.5 appears often when a correlation with velocity is attempted. Mecklenberg and Kubelka *(27)* were the first to explain the increasing rate constants with flow rate in packed beds in terms of the Nernst theory of a variable boundary-layer thickness. They found that the rate constant varied directly as the square root of the velocity.

TABLE 1.—LITERATURE SURVEY OF ADSORPTION AND ION-EXCHANGE KINETICS IN STATIC BEDS—RELATION OF FLUID VELOCITY TO RATE CONSTANTS

Investigators	Type of System	Solid Phase	Fluid Phase	Reynolds Number Range Covered,* $\frac{D_p \rho v}{\mu \epsilon}$	Variation of Rate Constant with Velocity,** (n in equation $k = \phi v^n$)
(*2*)	Ion exchange	14-28 mesh zeolite	Water, Mg^{++}, Ca^{++}	6 to 24	0.0
(*10*)	Ion exchange	20-30 mesh zeolite	Water, Cu^{++}	0.7 to 3.5	0.0
(*11*)	Adsorption	8-100 mesh carbon	Water, acetic acid	0.27 to 5.8	0.0 → 0.23
(*1*)	Adsorption	6-8 mesh silica gel	Water vapor, air	85 to 850	0.49
(*8*)	Adsorption	8-18 mesh carbon	Air—CCl_4	4 to 30	0.5
(*24*)	Jones reductor	16-60 mesh zinc	Water, $Fe_2(SO_4)_3$, $ZnSO_4$	0.5 to 35	0.5
(*13*)	Ion exchange	Sulfuric acid carbon exchanger	Water, Ag^+	0.9 to 4.0	0.5
(*22*)	Adsorption	40-80 mesh carbon	Water, acetic acid	0.05 to 0.97	0.5
(*4*)	Ion exchange	70-80 mesh Amberlite IR-1	Water, Na^+, CsCl	0.7 to 1.8	0.5 → 1.0
(*32*)	Ion exchange	14-30 mesh Amberlite IR-120	Water, Cu^{++}	3 to 6.7	0.7
(*5*)	Ion exchange	40-50 mesh Amberlite IR-1	Water, Rb^+, KCl	43 to 337	1.0

* ϵ assumed to be 0.4 when not measured. ** As interpreted by original investigators.

Considering the nature of the transfer process, one might intuitively predict that the exponent would range from 0 to 1. For a strictly diffusional transport at the lower limit of zero velocity, there will be no dependence on velocity and n is 0. At high velocities, the decrease in the thickness of diffusional boundary layer is approximately proportional to the mass velocity and n should approach a limiting value of 1.

Wilhelm (*34*) stated that transfer coefficients vary with velocity relative to the interface with an exponent ranging from 0 to 1. Data were presented from the work of Fisher (*14*) to substantiate the exponent of 1 in the turbulent region, but none was available for the laminar-flow region.

During recent years, mass transfer at a solid-fluid interface in packed beds has been actively investigated. Papers dealing with a gas phase are quite numerous (*9, 12, 18, 20, 21, 30, 33, 35*). Study of the liquid phase has been confined, thus far, to three principal papers: McCune and Wilhelm (*26*), Hobson and Thodos (*19*), and Gaffney and Drew (*16*). In all cases, the region below a Reynolds number of 1 was not investigated.

As a result of this work, correlations have been given which are subject to serious errors when extrapolated to low Reynolds numbers. Perhaps the most complete correlations have been recently reported by Gamson (*17*), but these are limited because of a lack of data in the laminar region. Yet, mass transfer in packed beds at low-flow rates is an important consideration in such commercial operations as adsorption and ion exchange.

Theory

As stated previously this study covers results of rates of solution of 2-naphthol and benzoic acid from solid spheres of these compounds into water. As such, the entire resistance to mass transfer can be attributed to the liquid phase.

Results are based on calculations involving the following concepts and assumptions, previously outlined by McCune and Wilhelm (*26*):

1. The effective driving force is a concentration gradient across a diffusional boundary layer surrounding the particles.
2. Solute concentration at solid-liquid interface is saturation value at mean temperature of system.
3. Low concentrations are involved at all points in system and simplifying assumptions will be made accordingly.

In addition, the following points are important in considering calculations in viscous-flow region:

1. No axial diffusion exists.
2. No free convection exists.

The rate equation for computing a film coefficient, based on the assumptions above and material balances, is well known and will be written without derivation. For a differential segment,

$$W dc = k a_t \Delta c \, dV \qquad (1)$$

This equation can be integrated between the inlet and outlet conditions of the bed of solubilizing particles, if constant flow around uniformly dispersed particles is considered. The integrated equation is:

$$W(c_2 - c_1) = k a_t \Delta c_{lm} V \qquad (2)$$

For these experiments, the inlet concentration of solute was zero, so that a convenient formula for computing k could be derived as follows:

$$\Delta c_{lm} = \frac{(c^* - c_1) - (c^* - c_2)}{2.3 \log \dfrac{c^* - c_1}{c^* - c_2}} \qquad (3)$$

If $b = c_2/c^*$, $c_1 = 0$ and $a = a_t V$, then substitution of these values in (3) and (2) gives

$$k = \frac{2.3W \log\left(\dfrac{1}{1-b}\right)}{a} \qquad (4)$$

Correlation of the mass-transfer coefficient with other principal variables of the system can best be done by the j factor of Chilton and Colburn (*6*).

Before giving the j factor expression, a definition is desirable for one of the dimensionless groups, the Reynolds number. By expressing the length term as a nominal particle diameter and the velocity term as an average interstitial condition within the bed, as done previously (*16, 26*), the Reynolds number is:

$$Re = \frac{D_p G}{\mu \epsilon} = \frac{6G}{S_o \mu \epsilon} \qquad (5)$$

By dimensional analysis, the following correlation equation for mass transfer in dilute solutions can be obtained, as first demonstrated by Chilton and Colburn (*6*) for turbulent conditions:

$$j_\epsilon = \frac{k\epsilon}{G}\left(\frac{\mu}{\rho D_m}\right)^{\eta} = q\left(\frac{D_p G}{\mu \epsilon}\right)^{m} \qquad (6)$$

The exponent, q, on the Schmidt number is generally accepted to be 2/3. Gaffney and Drew found $q = 0.58$ for Schmidt numbers ranging from 100 to 10,000 in liquid systems. The value of the exponent, m, which is equal to $n - 1$, is a function of the Reynolds number.

One of the difficulties in obtaining data at low-mass velocities in packed beds is to maintain a flow pattern through a finite depth of active (actively dissolving) solids and yet prevent saturation within the bed. This condition can be alleviated by proper choice of experimental conditions and materials, e.g., (1) large particles; (2) solute which can be assayed quite accurately; (3) a system having a high Schmidt number, and (4) a minimum depth of active solids.

To maintain a reasonable flow pattern where a shallow bed of active solids is required to prevent saturation, inert solids of similar geometry, such as glass or clay beads, can be placed on both sides of the active solids. It must be realized that concentration gradients in the voids surrounding an active particle will differ, depending on the activity or inertia of the surrounding particles.

Experimental Work

MATERIALS

The 2-naphthol-water system was selected as an ideal one for low-mass velocity studies. The 2-naphthol is only slightly soluble in water and accurate methods were developed for analyzing dilute solutions. The C.P. grade 2-naphthol used could be easily pelletized.

Distilled water was taken from a laboratory line and boiled to remove dissolved air. Boiling was used to prevent the formation of bubbles in the packed bed.

The benzoic acid-water system was studied as an independent check. Although somewhat easier to analyze, it was more soluble in water and pellets had to be changed more frequently. U.S.P. benzoic acid was utilized in this work.

PELLETS

The 2-naphthol powder was granulated by melting and pouring molten liquid into rapidly stirred water. Large lumps thus formed were air-dried and ground to the proper-size granules with mortar and pestle. Pellets were formed in a Eureka single-punch tablet machine made by the F. J. Stokes Machine Co. No lubricants or binding agents were necessary. The allowable nominal diameter of the pellets was 0.625 cm. ±0.015 cm. Surface area and volume of the pellets were computed from dimensions for the spherical end segments and a cylindrical middle section (0.21-cm. avg. thickness).

The surface of the new pellets was smooth and glossy. After several runs, the surface became covered with a fine powder of 2-naphthol. When this coating was brushed off, the surface had the same smooth appearance as the new one when viewed under a 10× glass. The pellets were reused until a maximum diameter decrease of 4% was obtained.

Benzoic acid pellets were formed with difficulty from the crystalline powder as purchased. No lubricant or binder was necessary. Although more soluble than the 2-naphthol pellets, the surface still remained smooth and glossy after a run. The diameter decrease was held below 4% by using new pellets for each run.

PHYSICAL CONSTANTS

Solubility and diffusivity data as a function of temperature for 2-naphthol were taken from the paper of McCune and Wilhelm (*26*). Solubility data at several temperatures were confirmed, using assay techniques described below.

For benzoic acid, data given by Linton and Sherwood (*25*) for diffusivity were used to calculate the Schmidt number. Solubility data for benzoic acid were taken from Seidell (*31*).

COLORIMETRIC ANALYSIS FOR 2-NAPHTHOL

The method employed by McCune and Wilhelm for analysis of dilute aqueous solutions of 2-naphthol consisted of a coupling reaction with benzene diazonium chloride. The resulting water-insoluble dye, whose concentration was measured colorimetrically, was rather unstable.

To eliminate this disadvantage, a more stable water-soluble dye, Orange II, was formed by coupling 2-naphthol with the sodium salt of sulfonated benzene diazonium chloride (*3*). The method can be used for assaying concentrations of 2-naphthol as low as 5 p.p.m. with a coefficient of variation of ±1.8%.

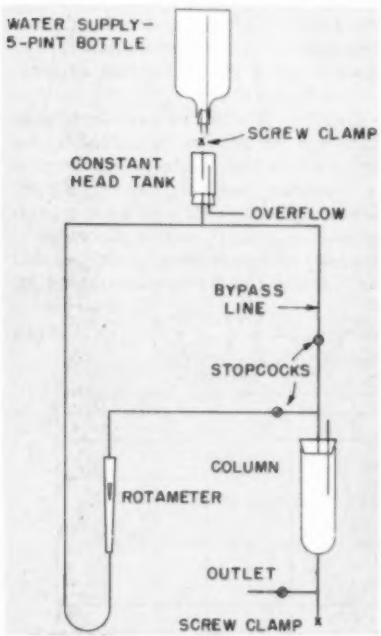

Fig. 1. Apparatus piped for downflow operation.

VOLUMETRIC ASSAY FOR 2-NAPHTHOL

The colorimetric analysis was replaced by a more direct volumetric technique during the latter part of this work.

The method was developed by Knowlton (*23*) for determining small concentrations of unsaturates suspended or dissolved in aqueous phase. It consists essentially of reacting 2-naphthol with bromine liberated by sulfuric acid from a potassium bromide-bromate solution for fixed time and temperature conditions. The unreacted bromine is determined by titration of iodine displaced from potassium iodide with sodium thiosulfate and starch. The coefficient of variation for this method is ±2.3% for solutions above 20 p.p.m. of 2-naphthol.

VOLUMETRIC ANALYSIS OF BENZOIC ACID

Samples were analyzed by titration with 0.025*N* NaOH using phenolphthalein as indicator. A standardizing plot was developed using known concentrations of benzoic acid.

APPARATUS

The apparatus used is shown in Figure 1. It consisted of a boiled-water reservoir, constant-head tank, rotameter, transfer column, and connecting lines of rubber and glass tubing. As pictured, the column is operating with a downward flow of water. By changing the lines, an inverted column was used for upflow studies.

The transfer column was made from Pyrex glass and had an I.D. of 9.69 cm. and a height of 26.6 cm. A large rubber stopper was used to close one end. This stopper had openings for the inlet stream, a thermometer, and a sampling tube (for upflow runs only). Three holes were made on the inside flat surface of the stopper to hold an upflow bed support consisting of bronze rods brazed to a stiff stainless steel screen.

OPERATING PROCEDURE

The column was partially filled with water and 6-mm. spherical glass beads were added to a predetermined level. Active pellets were then distributed evenly over the tops of the beads, making sure there were no air bubbles on any of the pellets. More glass beads were added, and the column was filled with water. The distribution of flow in such a packing was studied by a dye solution to insure adequate distribution of the inlet feed. To minimize holdup time, active pellets were placed as close to the outlet as possible, yet maintaining the required uniformity of flow.

The flow rate was determined by collecting and weighing several samples, the collecting time being measured with a stop watch. It was found that steady-state conditions were reached after about four times the void volume beneath the active pellets had passed the outlet. A sample of 35 to 120 ml. was collected for assay purposes any time after this established minimum.

TABLE 2.—RANGE OF EXPERIMENTAL AND CALCULATED DATA *

No. of runs: 44

Temperature: 19.0-28.5° C.

Schmidt No.: $\left(\frac{\mu}{\rho D_m}\right)$: 814-1147

Per cent of saturated solubility concentration in exit stream: 1.5-65.2

No. of active pellets used: 3-445

Flow rate (G): 0.50-277. lb. hr.$^{-1}$ft.$^{-2}$

Surface area per pellet: 0.00120-0.00135 sq.ft.

Mass-transfer coefficient (k): 0.233-5.26 lb. hr.$^{-1}$ft.$^{-2}\Delta c_{lm}^{-1}$

Reynolds No. $\left(\frac{DG}{\mu\epsilon}\right)$: 0.0125-7.21

*** Complete data may be found in Table 2a on file with A.D.I. Auxiliary Publications.**

The column was placed in a draft-free position, but no attempt was made to thermostat the air temperature surrounding the jacket. The temperature of the water was read by the thermometer inserted in the packed bed. Readings taken throughout the run showed a maximum spread of 0.2° C. for the runs reported. Samples from above the bed were drawn off immediately after the completion of a run to check for back diffusion.

Comment on Results

Table 2 * is a summary of the range of experimental and calculated values obtained for forty-four runs, using 2-naphthol and benzoic acid. Figure 2 is a plot of the data correlating the mass-transfer coefficient with Reynolds number by means of the j_ϵ factor.

Using upflow, the data were not reliable at $Re < 0.5$ because of back diffusion and free convection resulting principally from concentration gradients set up in the void channels. When downflow was employed, the correlation could be extended to Re of 0.1 before back diffusion was observed at a sampling point several centimeters above the active pellets. The average deviation of points representing downflow runs for $Re > 0.1$ from the probable correlation line for 2-naphthol is 7.9%. This compares favorably with a 7.7% deviation obtained by Gaffney and Drew. There was no statistical difference between runs made with the active bed thickness varying from one to four layers of pellets.

The free-convection effect has been extensively discussed by Gaffney and Drew. It was visually observed by Winterkamp (*36*), using slightly water-soluble dye pellets of 6-mm. diam. in a packed bed. At a critical Re of about 1.7 for his system, the dye moved down the column in streamers against the upflow of water. The concentration of dye in the calming section became so great that the glass beads were no longer visible. When employing downflow with the same constituents, no back diffusion was observed at Re down to 0.05.

The calculation of mass-transfer coefficients was based on the assumption that axial diffusion and density gradients were nonexistent. There should be no solute in the feed entering the active bed section. At low Re values, this condition does not exist because of an axial diffusion gradient toward the feed inlet. The true driving-force gradient in the active bed will be less; hence, the mass-transfer coefficient obtained will be low when using a larger driving-force gradient than actually exists. For this reason, the correlation curve should be extended smoothly to lower Re values, rather than having a marked reversal of curvature as shown by the dotted lines in Figure 2. Note that the slope of the

line can never become greater than −1. The benzoic acid data are all above the curve obtained for 2-naphthol. They form a smooth curve with slope of −1 which appears to converge with the 2-naphthol curve at a *Re* of 5. Linton and Sherwood (*25*) have observed this phenomenon for the same two systems at higher flow rates inside tubes. In their work, the high solubility of benzoic acid produced a rough surface which improved the transfer area. The surface of benzoic acid pellets in this investigation remained smooth and glossy.

Since free convection has been observed at low *Re* values, the introduction of the Grashof number for mass transfer under isothermal conditions seems plausible. This can be defined as a function of the density difference caused by a concentration gradient rather than a temperature gradient, *i.e.*,

$$Gr_m = \frac{D_p^3 \rho^2 g_c a \Delta c}{\mu^2} \qquad (7)$$

Since volume changes are negligible when adding small amounts of solute to most liquids, a has a value of 1. Using the other known properties of the two systems and an average of the concentration gradients for comparative purposes, the computation of the Grashof number for 2-naphthol-water runs averaged 200, while for benzoic acid it was nearer 10,000. This could explain the higher-transfer coefficients obtained for benzoic acid in the laminar region.

Figure 3 is a plot of the j_e vs. *Re* using data of this investigation, Gaffney and Drew, and Wilhelm and McCune. The agreement is excellent in the overlapping regions and, hence, a good correlation for two systems is presented which covers a range of *Re* from 10^{-2} to 10^4.

The correlation reveals the fact that the mass-transfer coefficient in packed beds varied with mass velocity raised to an exponent, n, which is a function of the Reynolds number itself. This can be seen by observing the average values of n marked for each cycle of *Re* in Figure 3. For this reason, the square root test for correlating mass-transfer data with velocity must be used with caution and only in the *Re* range where it applies.

Another observation is the effect of the Schmidt number. Figure 3 was prepared using the 0.58 exponent, as recommended by Gaffney and Drew, based on a correlation of liquids whose Schmidt numbers covered a range from 100 to 10,000. When the data for gases obtained by Gamson, Thodos, and Hougen, Wilke and Hougen, and Denton, Robinson, and Tibbs are plotted on the same figure, the gas data fall on a curve well above the established liquid curve. Some data of Hurt, Resnick and White, and Eichhorn and White fall below the other gas data, but show an effect of particle size not accounted for by the Reynolds number. Most data were replotted in Figure 4 using the 2/3 power of the Schmidt number originally proposed by Colburn. This produced a better correlation of most of the gas and liquid data. It is recommended that the Schmidt number exponent of 2/3 be used for the present, until much more data on packed beds are accumulated and examined. It is quite probable that the results will verify recent theoretical equations for heat and mass transfer which indicate that the exponent will vary with the Prandtl or Schmidt number.

A line for isolated spheres is also plotted in Figure 4. This was taken from data of Frossling (*15*) and Powell (*29*) as shown in Perry (*28*). As expected, mass transfer in the turbulent region for an isolated sphere is poorer than for a packed bed at the same Reynolds number. As the laminar-flow region is approached, the curves tend to coincide.

Three different lines are shown in Figure 4 for possible correlations below *Re* of 100. The lower two are based on the data for liquids reported in this paper. The upper one comes from the correlation recently proposed by Hobson and Thodos (*20*) using data for the vaporization of numerous substances into moving gas streams. Several explanations are possible.

Colburn (*7*) has shown that more than one correlation line exists for laminar flow inside tubes for analogous heat-transfer data. By rearranging the Graetz equation, which assumes a parabolic velocity distribution and absence of free-convection currents, he showed that the j factor for the laminar region is:

$$j = q \left(\frac{DG}{\mu}\right)^m \left(\frac{L}{D}\right)^p \qquad (8)$$

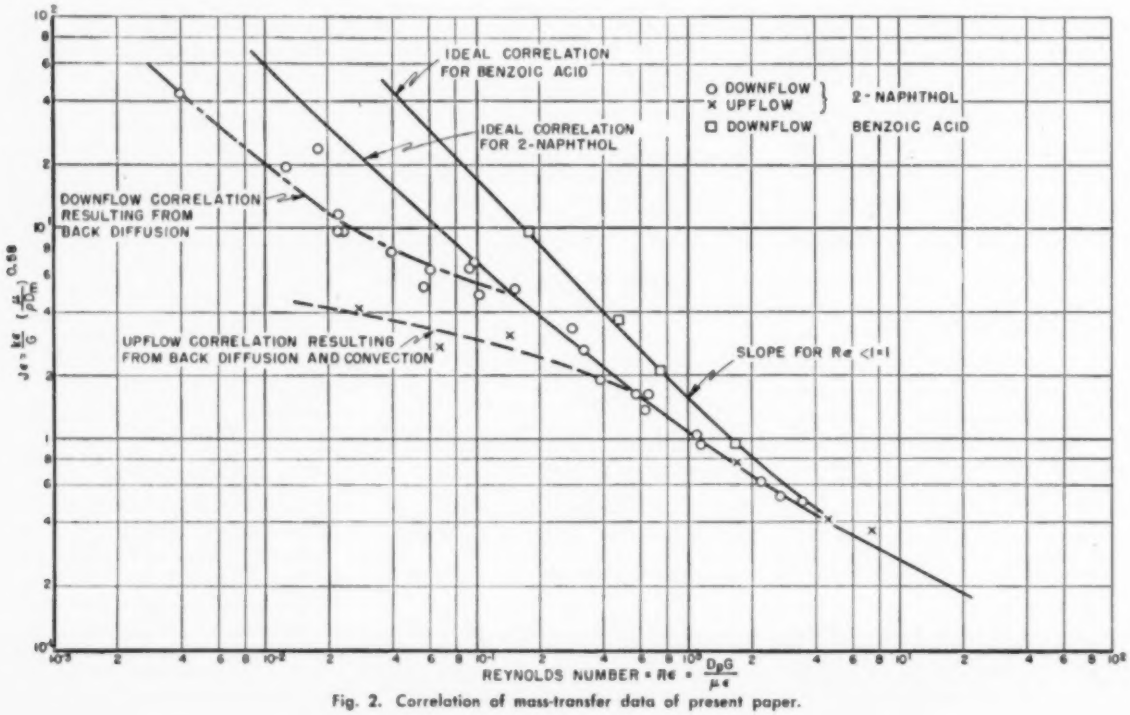

Fig. 2. Correlation of mass-transfer data of present paper.

The same analogy can be considered for packed beds, if the void space around the particles is visualized as a number of small-diameter parallel tubes. Each packing configuration will have a characteristic L/D ratio.

The existence of free-convection currents, which depend not only on the geometry of the system, but also on temperature and concentration gradients set up during the transfer of heat and mass, will cause differences among systems investigated. Much more data on the effect of Grashof number in packed beds are required before any theoretical or empirical methods of correlation can be tested.

These may be reasons why no single line should represent all mass-transfer data in the laminar region when plotting j_ϵ factors against a Reynolds number, a dimensionless correlation originally derived only for turbulent regions.

On examining the pellets from the mass-transfer runs, bumps or high spots were noticed in several experiments where the pellets were excessively solubilized. The high spots always occurred where points of contact were made among other active or inert pellets. This is to be expected, as there would be zero fluid velocity and slow diffusional transport at the contact surface. If there is any tendency for small nonspherical particles to agglomerate, or to have unusually high contact surface, the effective mass transfer will be considerably reduced from the value obtained if all of the surface were contributing equally. Gamson (*17*) took this phenomenon into account by introducing an empirically determined shape factor relative to a value of unity for spheres which present a minimum contact area. The determination of the effective surface area for mass and heat transfer, particularly for small particles, needs further study, since it may explain some of the differences which have occurred in the past when attempting to correlate transfer data for small particles.

Another significant variable which needs study is the effect of interfacial tensions on transfer data. This could conceivably dictate the flow pattern through small voids of varying size which occur when using irregularly shaped particles.

Results can be considered only a start in elucidating mass-transfer effects in packed beds at low Reynolds numbers. Because of the many controlling variables, which have been pointed out, and the difficulty of obtaining good data using present techniques, much effort of a theoretical and applied nature will be required before a satisfactory explanation of the laminar-flow region can be given.

Acknowledgments

The authors are indebted to the department of chemical engineering, Ohio State University, for financial aid in carrying out the experimental program, to Prof. Webster B. Kay for encouragement and advice throughout the investigation, and to Battelle Memorial Institute for funds made available to publish this manuscript.

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Notation

DIMENSIONAL SYSTEM

M = mass
θ = time
L = length
T = temperature

NOTATION AND DIMENSIONS

a = total active surface area of packed bed, L^2
a_v = surface area per unit volume of packed bed, L^{-1}
c = solute concentration, MM^{-1}
Δc = driving - force concentration gradient, MM^{-1}
c_1 = inlet solute concentration, MM^{-1}
c_2 = exit solute concentration, MM^{-1}
c^* = saturated solute concentration, MM^{-1}
D_p = nominal particle diameter, calculated as diameter of a sphere having same area as a pellet, L
D_m = mean diffusivity for undirectional diffusion, $L^2\theta^{-1}$
D = equivalent diameter of voids, L
g_c = gravitational constant, $L\theta^{-2}$
G = superficial mass velocity, $ML^{-2}\theta^{-1}$
G_m = superficial molal mass velocity, $ML^{-2}\theta^{-1}$

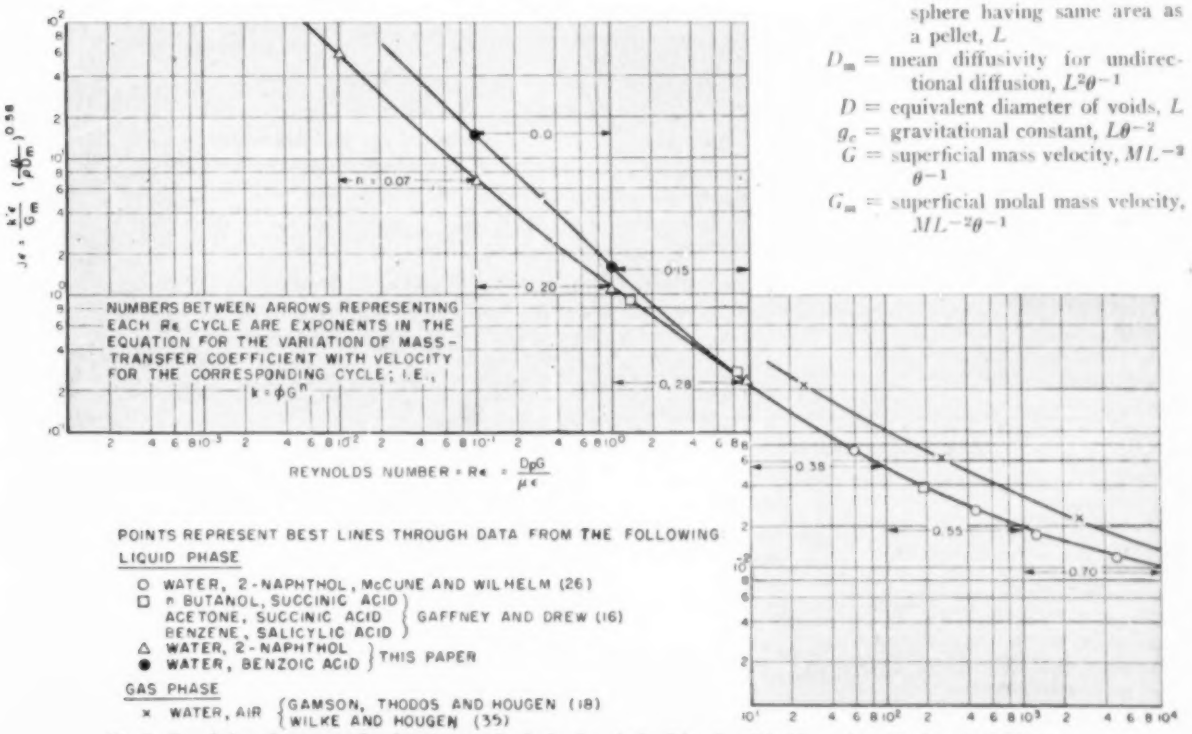
$j_\epsilon = \frac{k}{G}\left(\frac{\mu}{\rho D_m}\right)^{0.58}$
n = 0.07
0.0
0.15
0.20
0.28
0.38
0.55
0.70
NUMBERS BETWEEN ARROWS REPRESENTING EACH Re CYCLE ARE EXPONENTS IN THE EQUATION FOR THE VARIATION OF MASS-TRANSFER COEFFICIENT WITH VELOCITY FOR THE CORRESPONDING CYCLE; I.E., $k = \phi G^n$
REYNOLDS NUMBER = $Re = \frac{DpG}{\mu\epsilon}$
POINTS REPRESENT BEST LINES THROUGH DATA FROM THE FOLLOWING
LIQUID PHASE
○ WATER, 2-NAPHTHOL, McCUNE AND WILHELM (26)
□ n BUTANOL, SUCCINIC ACID
ACETONE, SUCCINIC ACID
BENZENE, SALICYLIC ACID
} GAFFNEY AND DREW (16)
△ WATER, 2-NAPHTHOL
● WATER, BENZOIC ACID
} THIS PAPER
GAS PHASE
× WATER, AIR {GAMSON, THODOS AND HOUGEN (18)
WILKE AND HOUGEN (35)

Fig. 3. Correlation of mass-transfer data in granular beds of packed solids using Schmidt number raised to the 0.58 power.

j = dimensionless factor for mass transfer

k' = liquid-film mass-transfer coefficient, $M\theta^{-1}L^{-2}$

$$k' = \frac{\text{lb. moles}}{(\text{hr.})(\text{sq.ft.})(\Delta c)}$$

$$k = \frac{\text{lb.}}{(\text{hr.})(\text{sq.ft.})(\Delta c)}$$

L = equivalent length of voids, L

Re = Reynolds number based on average interstitial pore velocity and nominal particle diameter = $\frac{D_p G}{\mu\epsilon}$

S_v = surface area per unit volume of solid pellets, L^{-1}

v = superficial linear velocity, $L\theta^{-1}$

V = volume of bed, L^3

W = mass-flow rate, $M\theta^{-1}$

GREEK SYMBOLS

α = coefficient of density change per unit density per unit concentration of solute added, $M^{-1}M$

ϵ = void fraction

φ, ϕ = mathematical coefficients

ρ = density, ML^{-3}

μ = absolute viscosity, $M\theta^{-1}L^{-1}$

EXPONENTS APPLIED

m = Reynolds number

p = L/D ratio

q = Schmidt number

n = velocity

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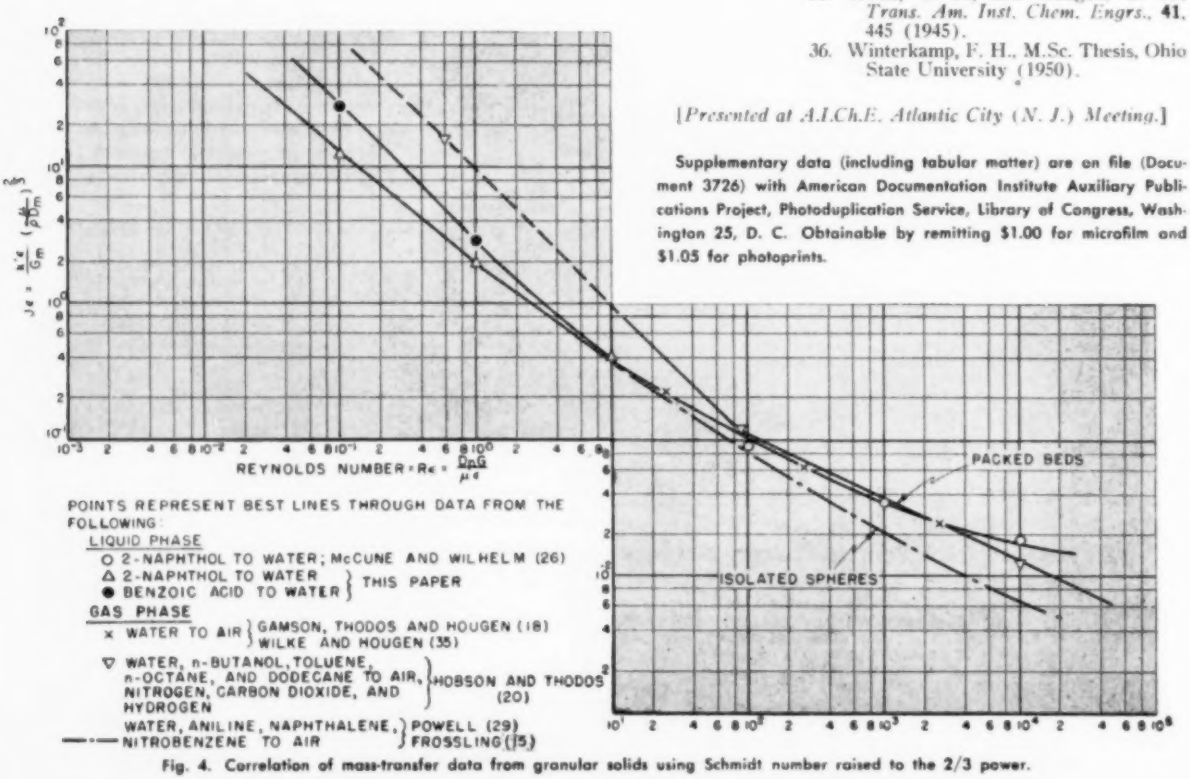
REYNOLDS NUMBER = Re = DpG/με
PACKED BEDS
ISOLATED SPHERES
POINTS REPRESENT BEST LINES THROUGH DATA FROM THE FOLLOWING:
LIQUID PHASE
○ 2-NAPHTHOL TO WATER; McCUNE AND WILHELM (26)
△ 2-NAPHTHOL TO WATER } THIS PAPER
● BENZOIC ACID TO WATER }
GAS PHASE
× WATER TO AIR } GAMSON, THODOS AND HOUGEN (18) WILKE AND HOUGEN (35)
▽ WATER, n-BUTANOL, TOLUENE, n-OCTANE, AND DODECANE TO AIR, NITROGEN, CARBON DIOXIDE, AND HYDROGEN } HOBSON AND THODOS (20)
WATER, ANILINE, NAPHTHALENE, NITROBENZENE TO AIR } POWELL (29) FROSSLING (15)

Fig. 4. Correlation of mass-transfer data from granular solids using Schmidt number raised to the 2/3 power.

Observations on the Design and Operation of High-Vacuum Systems

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This paper, nonquantitative in nature and presentation, covers observations and experiences derived from the development of a particular metallurgical process, but is intended primarily to be of general value to the engineers and others working with high vacuum for the first time. Particular attention is given to such subjects as: (1) static and dynamic vacuums; (2) mechanical and diffusion pumps; (3) leak detection; (4) gasketing; (5) oil purifiers for mechanical pumps; (6) diffusion pump fluids; (7) vacuum valves; (8) cold traps; (9) welding for vacuum service, and (10) cleanliness of the system.

C. Kerby Stoddard attended the universities of Nevada and Maryland, receiving a Ph.D. degree in chemical engineering in 1941. He was associated with the United States Bureau of Mines for approximately ten years in connection with extractive metallurgy of the uncommon metals, electrosmelting and electrometallurgy. Since 1948 he has been with the titanium division, National Lead Co., and more recently with its partially owned subsidiary company, the Titanium Metals Corporation of America, Henderson, Nev., as chief development engineer in the technical department.

William E. Mooz was graduated in June, 1950, from the Massachusetts Institute of Technology with a B.S. in metallurgy. He began work with the technical department of National Lead Co., titanium division, and gained experience with vacuum systems as an engineer associated with the titanium metal production plant. Further experience in this field was gained in the design of vacuum equipment for the Titanium Metals Corporation in Henderson, Nev. Mr. Mooz joined the Titanium Metals Corp. in August, 1952, and is a member of the technical department.

The use of high vacuum in industrial-production applications has been adequately described to the extent that it can safely be stated that the present-day chemical engineer is quite aware of this newest of the unit operations and is prepared to employ it on the required occasion. He will find the proper equations and basic data for his calculations on pumping speed, ultimate vacuum, production cycle, etc., in the current literature and manufacturers' pamphlets. He will probably enjoy the preciseness of his calculations and the adequacy of the information for design of the equipment. The manufacturers offer a choice of pumps, valves, gages, leak detectors and the specialties needed for a vacuum system and will aid him in choosing the components and fixing their relative arrangements. If he is a novice in the field of vacuum-producing they will offer him valuable advice based on experience. However, translating others' experience into one's own is frequently difficult. Practical difficulties usually beset the novice in vacuum practice before his apparatus attains the vacuum he is seeking since he has no basis on which to evaluate the advice he has been given. The rate at which things happen and the magnitude of relative importance of the various factors that enter into producing a vacuum may vary considerably from that described by others.

This paper will be concerned with the lesser things that affect the attainment of a high vacuum. Actually they are important since high vacuums are not obtained without due regard to them, but in comparison to the larger elements of design and engineering of the apparatus, such as equipment size, pump capacity, materials of construction, etc., they are likely to be disregarded or at least minimized. Hence, attention to the details early in the design and operating stages will save considerable avoidable delay. Their modification and adaptation to the application at hand will, of course, be required. The experiences discussed here

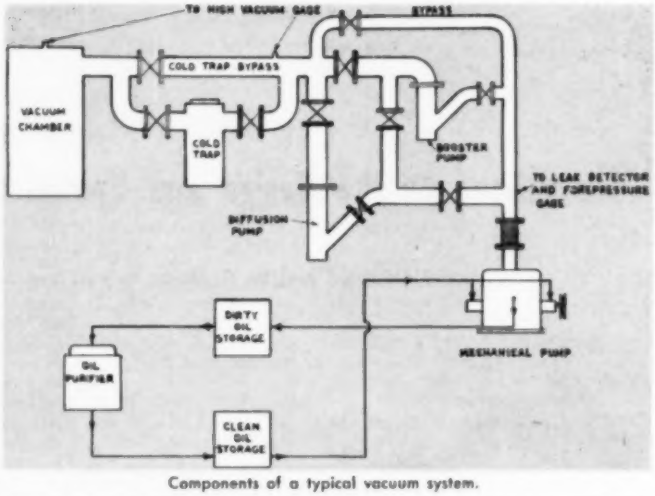
were obtained during the development of a process for the production of titanium. Vacuums in the range of 1 to 10μ were the ultimate generally attained; in some cases, the ultimate pressure was as low as 0.05-0.01μ. The use of titanium tetrachloride and its frequent presence in the system imposed severe contaminating conditions on the pumping apparatus that are not generally encountered in vacuum systems. A portion of the vacuum space was heated to a high temperature at which it was maintained for relatively long periods. Under these conditions the vacuum pressures mentioned before were attained and maintained.

In particular, the following subjects will be discussed from the standpoint of experience and relation to vacuum production in a production plant operated by nonprofessional operators and nonspecialized maintenance crews:

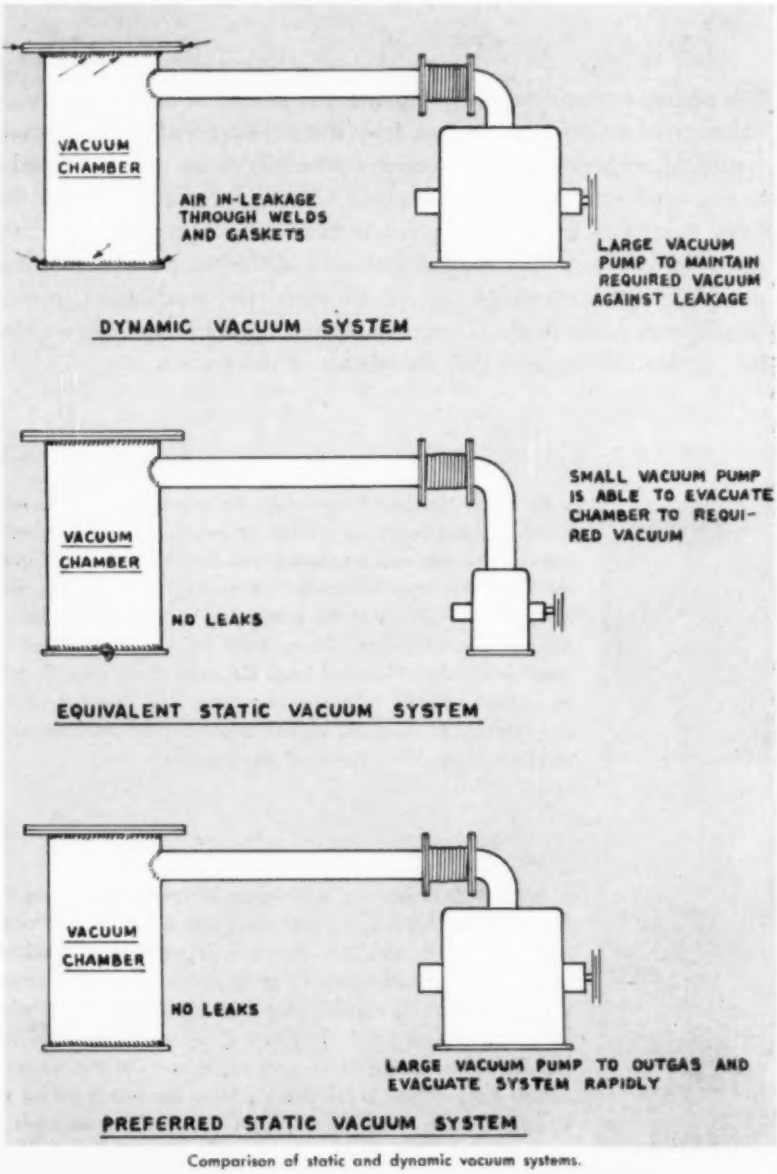
1. The difference between static and dynamic vacuum and its importance to process requirements.
2. The choice of mechanical and diffusion pumps from the standpoint of maintenance and operating difficulties with only a brief mention of the capacity factor.
3. The detection of leaks and its importance to process and maintenance costs.
4. Gasketing both large and small closures, piping and valves.
5. Use of oil purifiers for mechanical pumps.
6. Diffusion pump fluids from the standpoint of process requirements.
7. Use, repair and maintenance of vacuum valves.
8. The utility of cold traps.
9. Welding.
10. The cleanliness of the system and its relation to outgassing and pump downtime.

Static and Dynamic Vacuums

It is somewhat unusual to consider that there are two kinds of vacuums—static and dynamic. Neglecting outgassing for the moment, the static vacuum is obtained in a vessel free from leaks, while the dynamic vacuum is the result of the use of pumps sufficiently large to maintain the required vacuum against the inflow of air through fine leaks. Traditionally, the sealed-off type of equipment such as lamps, X-ray tubes, cathode ray tubes, electron tubes, etc., are examples of the static vacuum systems. These systems are generally small and quite clean and usually constructed of glass. The use of "gettering" techniques and the noncyclic use of the vacuum makes the creation of the vacuum simpler. Use of static vacuum for the production of pure metals imposes considerably greater difficulties when it becomes necessary to protect the metal from atmospheric oxygen and nitrogen pickup. Such are the requirements of



Components of a typical vacuum system.


VACUUM CHAMBER
AIR IN-LEAKAGE THROUGH WELDS AND GASKETS
LARGE VACUUM PUMP TO MAINTAIN REQUIRED VACUUM AGAINST LEAKAGE
DYNAMIC VACUUM SYSTEM
VACUUM CHAMBER
NO LEAKS
SMALL VACUUM PUMP IS ABLE TO EVACUATE CHAMBER TO REQUIRED VACUUM
EQUIVALENT STATIC VACUUM SYSTEM
VACUUM CHAMBER
NO LEAKS
LARGE VACUUM PUMP TO OUTGAS AND EVACUATE SYSTEM RAPIDLY
PREFERRED STATIC VACUUM SYSTEM

Comparison of static and dynamic vacuum systems.

zirconium and titanium. The complete elimination of leaks in large-scale-production equipment constructed of steel and ferrous alloys, and heated to temperatures of 800-1000° C. was accomplished in the case of these two metals. The elimination of leaks for attaining a static vacuum is like the proverbial rabbit pie —first you must find the leaks. This is virtually impossible without the proper equipment.

For this purpose, several models of the extremely sensitive mass-spectrometer type of leak detector are available. For halogen-free systems, the less expensive, positive-ion halogen-sensitive leak detectors are available. Dynamic vacuum systems are more generally used in large-scale apparatus since process requirements are not jeopardized in most applications by the presence of atmospheric oxygen and nitrogen in amounts 0.01-0.001% of that available at atmospheric pressure. Typical of such use of vacuum is the ferrosilicon or Pidgeon magnesium process wherein magnesium is distilled from the reaction mass as it is reduced from dolomite by ferrosilicon. Calcium is made in a similar way by the use of aluminum and lime. The vacuum casting of metals, the separation of metals by vacuum distillation are illustrations of the use of dynamic vacuums. The design of vacuum equipment for these processes is generally an easier job since care in construction and the elimination of the gross leaks by the soap-bubble technique generally produce the required degree of vacuum. This is especially favored by the growing realization that pumping capacity should be large in order to cut down on pumping time and process cycles. The inflow of oxygen, nitrogen, and water vapor through the minor leaks is not detrimental over long periods of time to the dynamic system, but generally cannot be tolerated for processes requiring static systems.

Mechanical and Diffusion Pumps

The size of mechanical pump required for a specific type of system may be determined by formulae supplied by pump manufacturers in their literature. It may be mentioned that an oversized pump may often be justified by the increased safety factor and pumping speed available. Rare indeed is the system which is not subject to sporadic outgassing, and it is of great advantage to have some reserve pumping capacity to meet an unexpected pressure rise.

Mechanical pumps are generally offered with either feather valves or poppet valves. Where relatively small volumes of noncorrosive gases are handled, the feather valves operate well. When larger gas volumes are to be handled, the poppet valves with their larger ports are preferred. Feather valves deteriorate more rapidly under the action of corrosive gases than do the poppet valves. For this reason, poppet-valve pumps generally require less maintenance. It was observed that steel feather valves give better performance in systems that tend to be dirty than plastic or teflon valves. It appears that the pieces of scale or dirt are crushed to a fine powder and quickly washed out of the valve surface by the pounding action of the steel valve surfaces, while they become partially imbedded in the Teflon strip and prevent the close seating of this valve.

Diffusion pumps are available from a wide variety of sizes and types. Originally, they were manufactured as laboratory or specialty items. More recently, the pumps are being offered with standard pipe flanges and more solid construction that is more compatible with large-scale industrial equipment. The use of standard pipe flanges is a distinct aid to the engineer. The choice of the booster pump vs. the diffusion pump is one well worth careful consideration. The higher ultimate vacuum that is afforded by the diffusion pump may not be required in many cases and its low limit on forepressure may cause unforeseen lengthening of cycle time in an outgassing system since even with an exceptionally large mechanical pump, hours may be consumed in pumping the system down to the pressure in which the diffusion pump can be put on the line. The booster pump will not yield quite as high ultimate vacuum as the diffusion pump but it can be started up much sooner during the pump down period. The use of the two types in parallel in the vacuum lines with suitable valves is quite satisfactory. This arrangement was used to attain short cycles with a system that was washed with hot water for cleaning. After atmospheric drying of the undrained water by the sensible heat in the steel vessel, complete drying and outgassing were rapidly accomplished with a booster pump. Previous to installation of the booster pump, hours were spent in pumping the system down to the limiting pressure of the diffusion pump. Vacuum technology would be benefited by the development of booster pumps that would operate against forepressures in the range of 5 to 15 mm. while preserving their great pumping speed.

Maintenance of diffusion and booster pumps was generally low and confined to routine cleaning. Heater burnout in some cases predominated and, generally, the pumps that are connected direct to the power line are preferred to those requiring a variable-voltage power input. Diffusion pumps operating under conditions of considerable fume and solids in the vapor stream showed almost no fall off of vacuum from an operating standpoint. Removal of the jet assembly for routine cleaning from pumps that were operating satisfactorily showed extensive encrustation. Ultimately, the pumps would have failed to give the required performance, but this was seldom experienced. The use of stainless steel in place of the usual soft aluminum for jet construction is an advantage when jet assemblies require frequent cleaning. In general, the diffusion and booster pumps are sturdy and dependable pieces of equipment for industrial use.

Leak Detection

Three good reasons for the importance of leak detection, and subsequent leak correction are the following: (1) rapid attainment of the required vacuum by the location and elimination of leaks, (2) recognition of outgassing when all leaks are located and eliminated, (3) prevention of detrimental effects upon quality of the product by the elimination of unrecognized leaks when static vacuum conditions are required.

Several methods of leak detection are available to the engineer, but to determine that there is a leak and where it is are quite different problems. The former is rather simple. One may either evacuate the system, read the pressure with a suitable gage, then isolate the system from the pumps with a vacuum valve and observe whether the system pressure rises over a period of time. By the same method, whether a leak exists or not may be determined by pressurizing the system. However, this may be time-consuming and even misleading when static vacuums are required since fine leaks may not be detected.

Locating the leak requires highly specialized equipment unless the leak is large. The helium-sensitive, mass spectrometer type of leak detector is sensitive and in operation quite sturdy. This type of leak detector is expensive, but is generally justifiable from the saving of cycle and maintenance time in producing and operating leak-free apparatus. On a small system, gross leaks may be located by pressurizing the apparatus and subsequently immersing it in water. Bubbles will indicate where the leak is. An alternate method is to use a soap solution which may be painted on the suspected areas. Again, bubbles indicate where the leak is. This technique is recommended for gross leaks that prevent the attainment of vacuums required for the operation of the diffusion pumps, which are generally lower than 200μ or 1000-1500 for some types of booster pumps. Vacuums below this range are required for leak detection that depends on in-leaks to transmit the helium or halogen gas issuing from the probe being used to locate the leaks. Under these

conditions, the better the vacuum the faster is the response of the detector when a leak is located. Best results are obtained with vacuums in the 10-1μ range.

The "sniffer"-type leak detectors are probably better adapted to leak-hunting since they depend upon out-leaks from the vessel pressured to 15-30 lb./sq.in. with air, or inert gases containing a few per cent of a halogen containing gas such as freon. In this case, gross leaks are detectable as well as the fine leaks since a high vacuum is not necessary. The mass spectrometer type of leak detector can be used for this application, in which case, helium is substituted for the halogen containing gas in the pressured vessel. Some models of this type of leak detector require an auxiliary vacuum pump and throttle valve on the "sniffer" for use in this manner. A discussion of the theory and quantitative use of leak detectors is given by Guthrie and Wakerling (*1*).

For systems containing halogens, the helium-sensitive mass-spectrometer-type must be used. This is relatively easy, once an operator has been properly instructed. The system is simply evacuated to 200μ or less, the leak detector put into operation, and a small jet of helium played upon the suspected areas, flanges, and valves. The influx of helium will be indicated on the meter and corrective measures then may be taken.

Rapid attainment of a high vacuum often may be an indication of a leak-proof system, but one should never make the error of not leak-checking. Detectable leaks have been found in systems maintaining a pressure of 1μ or less.

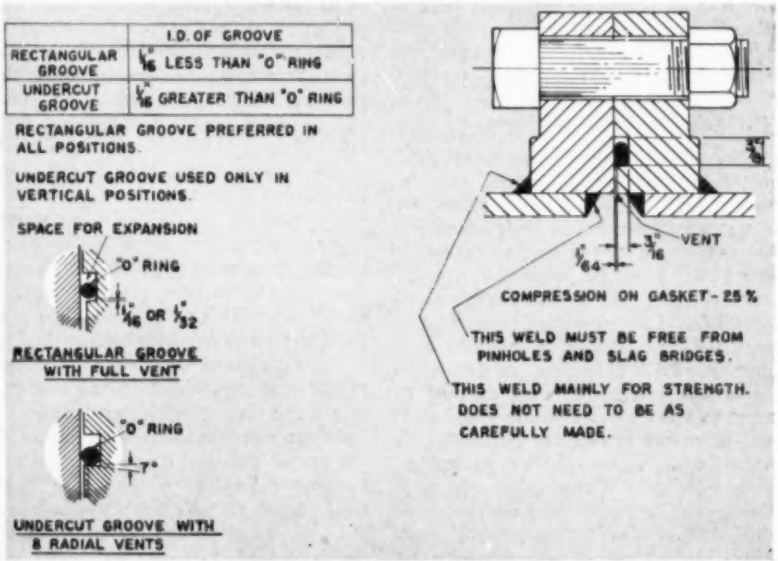
Gasketing

Gasketing of vacuum equipment requires more care than anything else. Unless the proper-type gaskets and gasket grease are use in the proper place, leaky joints will result. Cleanliness is a byword in the use of gaskets. The right gasket in the right place may still leak, like the proverbial sieve, if the gasket seat has not been properly cleaned. Flat gaskets were chosen initially in the application described here. At first red rubber sheeting was cut to full-face gaskets for pipe flanges, liberally smeared with vacuum grease (D.P.I. Celvacene) and the bolts tightened until the rubber partially extended. Hours of pumping with a 50-cu.ft./min. pump on a 15-cu.ft. system failed to produce the anticipated vacuum. The procurement of a leak detector showed that the flange gaskets were leaking. Then observation of such precautions as not using too much vacuum grease, and not compressing a gasket until no resiliency remained in the rubber, and conversion to unfilled neoprene rubber produced the proper vacuum. However, constant vigilance was required to prevent the untrained operators from tightening the bolts until the gasket leaked.

The conversion of gasketing to total use of 0-ring gaskets completely eliminated gasketing difficulties. All flanges were cut off the pipes and welded back on after machining square-sectioned grooves in one face to a depth allowing a 25% compression of the 0-ring gasket. The face inside the groove was machined a few thousandths of an inch below the outer flange face to permit the escape of gas trapped in the groove on the vacuum side of the 0 ring. In some cases, this was accomplished by radial slots. 0 ring gaskets are available in various formulations of rubber and neoprene as well as silastic, in diameters up to 16 in. Generally, 60 durometer (*A* scale) neoprene was specified although silastic was used on occasion for a cold trap when it was suspected that the neoprene cooled to a point where it no longer had sufficient resiliency. For diameters greater than 16 in., 0 rings can be made up from $\frac{3}{8}$-in. and $\frac{1}{2}$-in. diam. rubber or neoprene stock known in the trade as "rope." Vulcanized joints are superior to cemented ones. This is readily done in a split mold using a diagonally cut joint to accommodate the cross section of the rope, and even more satisfactorily done by a jobber or small specialty gasket firm since some experience is required in cutting the rope to the right length to get an 0 ring gasket of the correct diameter. 0 ring gaskets up to 42 in. in diam. have been used that were made in this manner with less than one per cent vacuum failure.

The installation of the 0 rings in the grooves is a simple matter. If the larger-diameter gaskets do not rest evenly in the groove, the simple precaution of storing them in a warm room will make them limp enough to lie uniformly in the groove and save considerable time of assembly. On cyclic-production operation this is important. Vertical joints can be made up with the 0 ring slightly undersized so that it is snapped into the groove and holds itself in place. In this case, radial outgassing slots on the inside face are preferred to the gap between the inside flange faces. Bolts are drawn up tight and used only in every other position or less if feasible. Since the flange faces match metal to metal, over-compression of the gaskets is impossible and operation is facilitated. The gaskets should be coated only lightly with vacuum grease which is wiped off after applying. This will leave just the right amount of lubrication. Gaskets that have taken on a permanent set can be frequently reclaimed by soaking them in carbon tetrachloride and steaming them out. This cannot be done, however, if the rubber shows any signs of cracking.

If the use of flat gaskets is unavoidable, neoprene should be used. The flat metal surfaces in contact with the gasket must be machined to remove any imperfections or uneveness on the faces. The gasket to be used should be given a light coating of Celvacene vacuum grease and then wiped with a clean, dry cloth to remove all but a thin layer of the grease. This step is essential to prevent the grease from squeezing into the system. Celvacene grease is prone to absorb helium, and should a helium-sensitive leak detector be used, additional time would be required to outgas the helium from the grease before leak detection could be attempted. The flanges on


I.D. OF GROOVE
RECTANGULAR GROOVE
1/16" LESS THAN "O" RING
UNDERCUT GROOVE
1/16" GREATER THAN "O" RING
RECTANGULAR GROOVE PREFERRED IN ALL POSITIONS.
UNDERCUT GROOVE USED ONLY IN VERTICAL POSITIONS.
SPACE FOR EXPANSION
"O" RING
1/16 OR 1/32
RECTANGULAR GROOVE WITH FULL VENT
"O" RING
7°
UNDERCUT GROOVE WITH 8 RADIAL VENTS
VENT
1/64
3/16
COMPRESSION ON GASKET - 25 %
THIS WELD MUST BE FREE FROM PINHOLES AND SLAG BRIDGES.
THIS WELD MAINLY FOR STRENGTH. DOES NOT NEED TO BE AS CAREFULLY MADE.

Details on use of "0" ring gaskets.

either side of the gasket should be inspected for specks of dirt, etc., and then uniformly tightened to provide an even pressure distribution on the gasket. If the joint is to be broken frequently, the gasket should be examined each time for signs of permanent distortion. If any signs are evident, the gasket should be replaced.

Oil Purifiers for Mechanical Pumps

The oil purifying unit is an almost indispensable auxiliary to the mechanical pump. This fact is easily overlooked and frequently much labor- and time-consuming effort is expended in trying to produce a high vacuum with a mechanical pump operating with a contaminated oil. The fundamental principles of the operation of a mechanical vacuum pump are based upon a sealing fluid of low vapor pressure. Yet many vacuum pumps are expected to produce high vacuums with contaminated oils having high vapor pressures. An occasional oil change produces improvements; usually they rapidly become contaminated again. Since vacuum pumps are actually compressors forcing vapors and gases into the atmosphere from the low pressure chamber being evacuated, there is little basis to expect the oil to resist absorbing contaminating vapors when they are squeezed against it.

Oil purifiers perform the useful service of removing the high vapor-pressure contaminants that are dissolved or emulsified in the mechanical vacuum pump. In the case of only moisture contamination, simple heating will help greatly. However, gradual oxidation and deterioration of the oil may develop high vapor pressure that is accelerated by continued heating. In the case of severe contamination by organic and acidic vapors causing sludging and breakdown of the vacuum oil, excellent performance was obtained by a purifying unit that subjected the dirty oil to a rough vacuum (27-in. Hg gage) distillation at 300° F., and subsequently filtered the oil through a bed of Fullers earth. In actual experience, the installation of a unit of this type eliminated frequent pump freeze-ups and inability to attain required vacuums. Mechanical pump troubles virtually ceased when the oil purifier was installed. Systematic and scheduled renewal of the filter bed is required but generally operators learn that attention to the oil purifier will save considerable operating trouble with the vacuum pumps.

Diffusion Pump Fluids and Valves

Experience with silicone diffusion-pump fluid indicates that there is much to recommend it for industrial applications. For cyclic operations in which the vacuum is frequently broken, this type of fluid is particularly suitable, since it resists the breakdown and oxidation that occur when operating errors cause exposure of the diffusion-pump fluid to air while it is still at operating temperatures. Silicone fluid has considerable chemical inertness to reactive chloride vapors, passing these through the system without apparent loss of effectiveness. The dirty and fouled fluid removed from the pump for cleaning is readily recovered by mixing it with diatomaceous-earth-type filter aid and filtering it through a laboratory Buchner filter. Valuable silicone oil is readily reclaimed this way. In comparison to the less stable organic fluids, the silicone diffusion-pump fluids offer considerable advantage in these characteristics.

The literature shows that a relatively large number of vacuum valves are available for installations, and have been generally designed to present large straight-through port openings that offer the minimum diffusional resistance to the gas flow. Generally, the valve stem seal is accomplished by means of a metallic bellows, but one design uses O rings and vacuum grease around the stem of a specially linked butterfly disk. Much ingenuity has been shown in constructing these valves; hence they are expensive in sizes of 6 in. and more.

Experience has been obtained with diaphragm valves for vacuum service and excellent performance is reported. Two types are available: closure being obtained by forcing the diaphragm against a bridge or dam mounted beneath it, and a Y-shaped construction in which closure is obtained by a more or less conventional disk and seat arrangement with a diaphragm valve-stem seal. Both kinds have been used in sizes up to 6 in. without leakage or diaphragm collapse from the atmospheric load. Maintenance on this type of valve has been inconsequential involving an occasional diaphragm or disk replacement. The disk-type valves were given a slight refinishing of the seat before use in the valve shop of the maintenance department to lessen the pressure needed for vacuum-tight closure. This type may have a slight advantage over the dam type of diaphragm valve since the finish is generally that of a rough casting. Greater closure pressures are required as a result and leakage, because of too much pressure, is possible.

Where it is necessary to use other than a vacuum-type valve for special purposes, such as nonvacuum tight isolation of parts of the equipment, special precautions must be taken to prevent atmospheric leaks. The valve must be blanked off and leak-tested for porous castings before installation. In use the valve-stem packing must be regularly inspected and replaced when necessary. Rubber bushings with thin punched Teflon disks on either side give excellent vacuum tightness and resist corrosive gases. However, frequent replacement is required because of the difficulty of lubricating the stem movement through the rubber bushing and the tendency of seizure to damage it.

Cold Traps

The use of refrigerated cold traps in any vacuum system is advantageous to prevent contamination of the vacuum-pump oil and to increase the pumping capacity in the system. The design of a cold trap is, of course, dependent upon the type and quantity of the vapor to be condensed and the pumping rate used. Aside from the theoretical sizing of a trap two important facts should be taken into consideration. The gas passage in the trap must have sufficient exposed area that the condensate will not form an insulating layer on the cold surfaces. In use, it is always desirable to maintain a slow pumping rate through the trap at the beginning of evacuation, so that the trap will not be subject to a heavy load and fail to precipitate all condensables. It is possible to include a flow-limiting orifice in the cold trap but this feature becomes objectionable as soon as all vapors are condensed and a high pumping speed is desired. In all static systems, the installation of a cold-trap by-pass line is advisable. Should this by-pass be omitted, it will be found that when the partial pressure of the condensable vapor in the evacuated chamber reaches a value lower than the vapor pressure of the condensed vapor in the cold trap, more of the contaminant will be removed from the trap than enters it. To leave the trap in the system is a waste of refrigerant as well as an impairment of the pumping efficiency.

It is usually advantageous to provide a cone-shaped bottom for the trap and equip it with a drain plug. By draining the cold trap of condensed water vapor, after it has warmed up it will not normally be necessary to disassemble and clean out the trap after each usage.

Refrigerants used in cold traps depend upon the required temperature in the trap. For many purposes, brine may serve, but attainable temperatures are limited. A good refrigerant for intermittently used traps consists of equal volumes of mineral spirits and CCl_4, and chipped dry ice. This solvent mixture is much safer to use than the very volatile and inflammable acetone and is less noxious than the frequently recommended trichloroethylene. This mixture gives a temperature of about −100° F. Where a mechanical refrigerating system is to be used, an ethylene glycol and water mixture or mineral spirits may be used as a refrigerant.

The engineer should beware of the fallacy that several cold traps in series at different temperatures may be used to collect different condensables. A combination of this sort is equivalent only to the cold trap with the lowest temperature, owing to the fact that the other traps will be "pumped" out by the low-temperature trap.

Welding

Vacuum welding is an art, and a highly refined one at that. Good welders are capable of producing a welded seam or joint which is both mechanically strong and leak-tight if they remember that the weld metal must be flowed across the seam continuously without applying too much weld metal and without breaking the arc, if possible. It is particularly important not to apply too much weld metal when the welded area is to be subject to high temperatures. If this procedure is followed, the chances of the weld cracking after it has been heated are reduced. Of course, the welding rod used must be of the same composition as the material to be welded. After a weld is completed, it should be leak-checked either by using pressure and soap solution as previously described, or by using a suitable leak detector. If a leak is found, the weld should be ground off to the base metal and a new weld made. This also applies to welds which have cracked during service. The supposition that applying another layer of weld metal over the original leaking weld will correct the situation is fallacious. Leaks are seldom corrected this way, and stresses are likely to be set up which will cause a new crack upon heating. In all vacuum welding it is advisable to use small-diameter welding rods. This minimizes the crater size and the amount of heat required. Commercial vacuum welding is done often by two welders operating as a team. When the rod used by one welder becomes depleted, the second welder picks up the arc immediately so that there will be no break in the weld to cause a leak later.

Cleanliness of the System

The importance of a clean system with regard to outgassing and pump down-time cannot be emphasized too strongly. All parts of the vacuum system must be scrupulously inspected for rust, scale and other foreign materials which are capable of adsorbing large quantities of gas and water. Maintaining clean equipment is a laborious task, but can be easily justified by the production time saved. It has been the writers' experience that a certain clean, dry system would outgas and pump down to a pressure of 100μ in a matter of minutes. The same system, improperly cleaned, outgassed for as long as 4 hr. before reaching the 100μ level. This loss of time cannot be easily justified in any production unit, particularly where quality may also be affected.

In any system where heat is to be applied to the evacuated apparatus, outgassing may be hastened by raising the temperature of the apparatus to 100° C. or higher. Cold traps should always be chilled before their insertion into the system in order to take advantage of their pumping speed during the outgassing operation.

In cases where the system pressure decreases slowly, and does not attain a low enough pressure for leak-detector operation, outgassing may be distinguished easily from a gross leak. This is accomplished by suddenly chilling the cold trap of a thermocouple-type vacuum gage (or other gage which records total pressure) with dry ice or liquid air. If the system is outgassing, a sudden reduction in pressure will be indicated by the gage as the nonpermanent gases condense in the cold trap. No reduction, or only a slight reduction in the indicated pressure, is evidence of a large leak.

Acknowledgment

The authors wish to express their appreciation to the management of the National Lead Co. for permission to publish this material.

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Guthrie, A., and Wakerling, R. K., "Vacuum Equipment and Technique," McGraw-Hill Book Co., New York (1949).

Discussion

E. A. Guldenzoph (The Dow Chemical Co., Midland, Mich.): In recent calculations it has been my observation that you can vary the velocity through pipe work from pumps over quite a range without materially affecting pressure drop, and yet it seems there should be some reasonable maximum design velocity. I understand that 5,000 cm./sec. or about 10,000 ft./min. is a maximum obtainable velocity if L/D ratio is 3 or less. Of course, allowable pressure drop must be considered and calculated by Poiseuille's equation adapted to low pressures.

C. K. Stoddard: Presumably you are concerned with the diameter of the pipes with which you connect up your vacuum system. We did not discuss that. It is our feeling that the available literature adequately points out the need for large diameters in the piping and we rather scrupulously endeavored to keep our pipe sizes as large as possible. We didn't concern ourselves with velocity particularly—we were more concerned with getting the piping into given spaces allotted for our equipment and the relative arrangements that we had available. I can't stress too strongly the need to have the pipes large. I have seen any number of installations where you have sensed that there was a tendency to make the pipes small. That is distinctly a step in the wrong direction. If the vacuum pump or diffusion pump that you use comes with a 6-in. diam., by all means continue that diameter to your apparatus. It's also good to continue the outlet of the diffusion pump in piping of the same diameter or even larger, to your mechanical pump and then reduce down to the inlet of the mechanical pump.

R. A. Koehler (General Electric Co., Schenectady, N. Y.): With reference to a heat-transfer medium in cold traps using dry ice our safety engineers urge us to avoid use of acetone, trichlor, and so on. We have found there is available a very low viscosity silicone oil which serves the purpose of heat-transfer medium. Now the mixture of dry ice in the silicone results in a temperature no lower than the dry ice itself as is the case, say, with acetone. But if the temperature of dry ice chips is adequate then we found the silicone oil is quite inert—quite safe—which far out-weighs any additional expense.

C. K. Stoddard: Our problem in connection with cold traps led us to consider silicone oil, too, but dismissed it because of the expense. Our cold traps were approximately the size of a 50-gal. drum.

C. R. Bartels (E. R. Squibb & Son, New Brunswick, N. J.): Have you ever used welding for strength and brazing, or silver soldering for vacuum tightness?

C. K. Stoddard: On one occasion we had to have the welders braze all the joints. That was at a location in a plant other than the one with which I was associated. That was done when local welders were incapable of producing a leak-free joint. They simply brazed everything up and it seemed to work satisfactorily.

L. W. Hull (F. J. Stokes Machine Co., Philadelphia, Pa.): On distinguishing between outgassing and air in-leakage—the application of a refrigerant to minimize outgassing is sometimes inconvenient. It depends on the design of the system. A simple way to detect air in-leakage is to make a record of the pressure-rise rate starting at high vacuum and going on into a few hundred microns or even to millimeters. If the difficulty is the result of outgassing, and not of air in-leakage, the pressure-rise rate will drop as the system pressure rises. If it remains constant from the low point on up, then it is obviously air in-leakage. Is that in line with your findings, Mr. Stoddard?

C. K. Stoddard: We used that in some of the early work in an operating plant where the operator in the production department was trying to get the thing back on the line. However, we didn't get far when we suggested use of that method. The operators were not of the technical caliber to keep the records and interpret the results. The outgassing was usually a condition we could not avoid. Finally, the installation of a large capacity booster pump (KB-300) solved that problem satisfactorily.

(Presented at A.I.Ch.E. French Lick, Ind., Meeting).

End of Vacuum Engineering Series

Sulfur from Hydrogen Sulfide

B. W. Gamson and R. H. Elkins Great Lakes Carbon Corp., Morton Grove, Illinois

A review of the literature on the conversion of hydrogen sulfide to elemental sulfur is given. The thermodynamics of the formation of sulfur from hydrogen sulfide is developed. A rigorous and unique calculation procedure is outlined. Limitations of literature-suggested calculation techniques are described. Restrictions on the design of units for this conversion are reviewed and the adaptations of the Claus process studied. Original kinetic and yield data on the oxidation of both hydrogen sulfide and carbonyl sulfide are presented.

In recent years the depletion of pure sulfur deposits capable of being mined by the Frasch process and the accelerated use of high sulfur-bearing petroleum crudes and natural gases have focused attention upon augmenting sulfur supplies from waste hydrogen sulfide.

Processes for the recovery of sulfur from hydrogen sulfide occur in variety as well as volume in the literature of the past twenty-five years. Most of these methods depend on the oxidation of the hydrogen sulfide, either directly or indirectly according to the reaction:

$$H_2S + [0] \rightarrow H_2O + S$$

This reaction may be carried out under a variety of conditions and with many different oxidizing agents.

Commercially, the most successful of these methods depends on the vapor-phase oxidation of H_2S with either air or SO_2. These oxidations are essentially high-temperature reactions and may occur at lower temperatures only on surfaces or in solution (*16*). Thus at 250-350° C., the reaction

$$H_2S + \tfrac{1}{2}O_2 \rightarrow H_2O + S$$

was found to proceed entirely on the walls of the vessel and best on glass, Al, or Al_2O_3. When the walls were coated with copper, the reaction was stopped almost completely (*15*). This was confirmed kinetically by Taylor and Wesley (*14*), who showed that the oxidations occurred only by contact catalysis below 730° C. Numerous proposals for catalysts for these reactions appear in the literature. These include Al_2O_3, activated carbons, silica gel, silicates of Al^{+++} and Fe^{+++} and the alkali and alkaline earth metals, metal sulfides, and alkaline compounds (*5, 6*). Of these, bauxite appears to be the most important. It combines low cost, durability and high activity (*5*).

The earliest commercialization of the vapor-phase oxidation was the Claus process, developed about 1890 and from which most modern processes have evolved. The process comprised the oxidation of hydrogen sulfide with air over a bauxite or iron ore catalyst in a single reactor. It was recognized that the lower the operating temperature, the greater the yield. Since radiation was the only provision for removing the large quantity of heat evolved in the process, the temperature was controlled by restriction of the space velocity. In order to achieve yields of 80-90%, only two to three volumes of hydrogen sulfide (S.T.P.) could be converted per volume of catalyst per hour. Thus, the greatest process design problem stems from the highly exothermic nature of the reaction.

The first significant advance in the art was made about 1937 by the I. G. Farbenindustrie (*2, 3*). Instead of burning the hydrogen sulfide directly over the catalyst, one third was burned completely to sulfur dioxide under a waste heat boiler. The sulfur dioxide was then reacted with the remaining two thirds of the hydrogen sulfide over bauxite at 700-750° F. The improvement in this modification may be seen by comparing the heats of the reactions involved.

Waste Heat Boiler

$$H_2S + 3/2\ O_2 \rightarrow H_2O + SO_2$$
$$\Delta H = 124\text{-}138\ K \text{ cal.}$$

Catalytic Converter

$$2H_2S + SO_2 \rightarrow 2H_2O + 3/eS_e$$
$$\Delta H = 21\text{-}35\ K \text{ cal.}$$

Over-all Combustion Single Reactor

$$3H_2S + 3/2\ O_2 \rightarrow 3H_2O + 3/eS_e$$
$$\Delta H = 145\text{-}173\ K \text{ cal.}$$

Thus only about one fifth of the total heat of reaction is evolved in the catalytic converter, so that the operating temperature can be maintained at sufficiently low levels with greatly increased space velocities.

A third development basic to many modern processes was initiated by the I. G. Farbenindustrie at about the same time as the previous modification (*1*). This process comprised the high temperature (up to 1000° C.) noncatalytic combustion of hydrogen sulfide with air in stoichiometric or greater proportions to produce sulfur directly in yields assertedly as high as 60-90%. The combustion may be carried out in a free flame or over an inert contact mass. The high-temperature combustion may be followed by one or more Claus catalytic converters to recover effectively all the sulfur.

Theoretical Analysis

The experimental evidence and theoretical data available in the literature relative to the mechanism of the selective oxidation of hydrogen sulfide to elemental sulfur are meager. Because of this, many different process arrangements combining free-flame combustion and Claus catalyst chambers have been proposed without equivalent results. The theoretical problem is somewhat complicated because of the numerous species of gaseous sulfur present, and the existence of competing reactions.

At temperatures above about 1200° K., and below about 2000° K., the sole stable molecular specie of sulfur is the diatomic form. Below 1200° K. and above about 300° K., a complicated equilibrium exists between S_8, S_6 and S_2, the composition depending upon the temperature and total sulfur partial pressure. Preuner and Schupp (*13*) reported extensive

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data on the vapor density of sulfur.* Kelley (*11*) reviewed their data, and calculated the free energy changes for this equilibrium. Based upon the calculated equilibrium constants, the systematic variation of S_8, S_6 and S_2 with both temperature and pressure have been developed and are presented in Figures 1, 2 and 3. Recently Klemm and Kilian (*12*) repeated the work from 450 to 850° C. with more modern equipment and obtained slightly higher molecular weights than did Preuner and Schupp. However, Klemm and Kilian's work was interrupted by World War II in Germany, and their data are presented as a progress report. Accordingly, the current study was predicated upon the results given in Figures 1, 2 and 3. Figure 4 represents the type of variation obtained between the various molecular species of sulfur at 1 atm. total sulfur pressure above the boiling point of sulfur and the saturated vapor pressure below.

The stoichiometric reaction which most simply represents the oxidation of hydrogen sulfide is given below,

$$2H_2S + O_2 \rightarrow 2H_2O + S_2 \qquad (1)$$

This expression is conditioned by the secondary sulfur specie equilibria,

$$S_6 \rightarrow 3S_2 \qquad (2)$$

$$S_8 \rightarrow 4S_2 \qquad (3)$$

Although Equation (1) represents the stoichiometry of the reaction, other reactions occur in the complex reaction equilibria and may be indicated by the following,

$$2H_2S + 3O_2 \rightarrow 2H_2O + 2SO_2 \qquad (4)$$

$$2H_2S + SO_2 \rightarrow 2H_2O + 3/2S_2 \qquad (5)$$

$$S_2 + 2O_2 \rightarrow 2SO_2 \qquad (6)$$

The thermodynamic-equilibrium constants for reactions (1), (4) and (6) are so great at the free-flame-combustion temperatures that no elemental oxygen exists in the reaction mixture. Accordingly, the actual equilibria can be calculated from a consideration of reactions (2), (3) and (5). Since the combustion of hydrogen sulfide occurs with air in accordance with the stoichiometry of Equation (1), the equilibria are further conditioned by Equations (7) and (8)

* Since this paper was written, Dr. James R. West has called the writers' attention to a more recent publication by Braune, H., Peter, S., and Nevelling, V., "The Dissociation of Sulfur Vapor," *Z. Naturforschg., 6a, 32-37* (1951). This paper reports the existence of four molecular specie, namely, S_{10}, S_8, S_6 and S_2. Preliminary calculations in critical temperature regions indicate that the yield of sulfur based on the Preuner and Schupp data gives fair agreement with the new data.

Fig. 1. Variation of diatomic sulfur with temperature and pressure when the total pressure is due to sulfur.

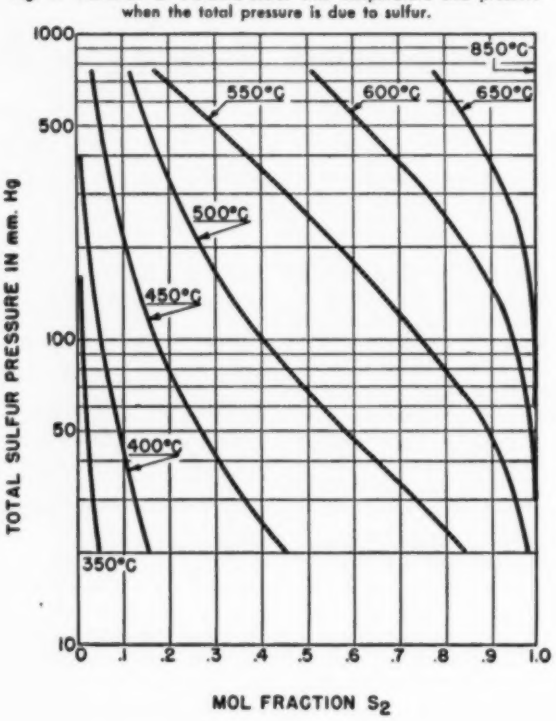
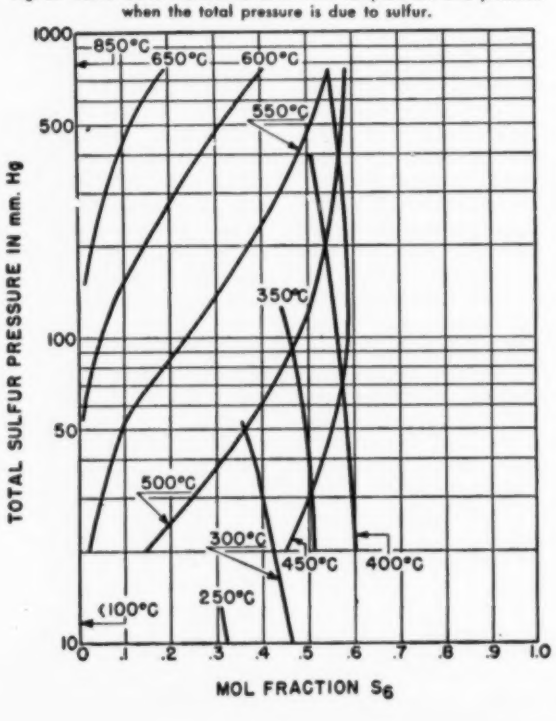


Fig. 2. Variation of hexatomic sulfur with temperature and pressure when the total pressure is due to sulfur.



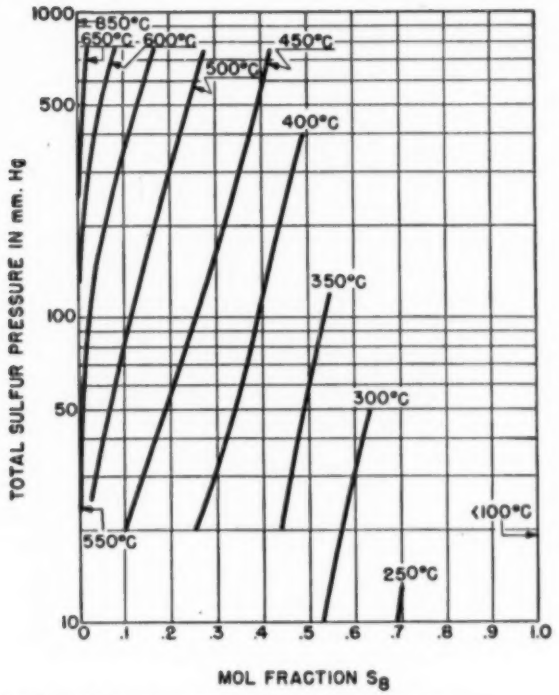


Fig. 3. Variation of octatomic sulfur with temperature and pressure when the total pressure is due to sulfur.

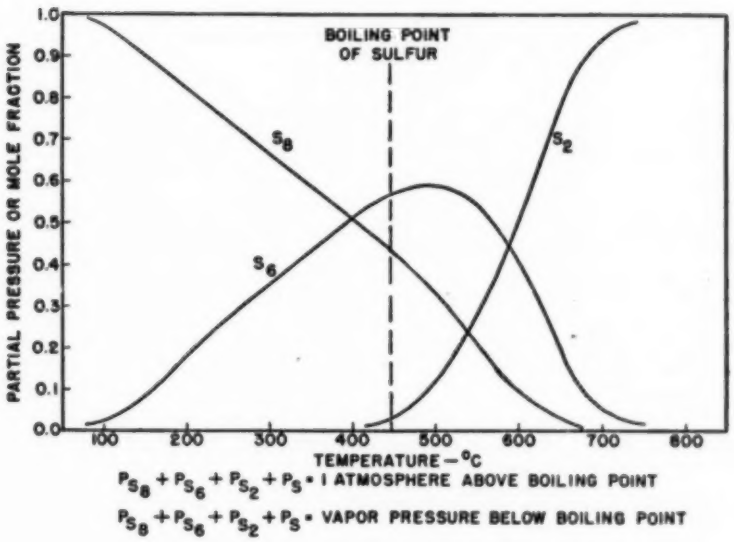


Fig. 4. Equilibrium between the molecular species of sulfur.

relating the partial pressures of nitrogen to the oxygen-containing gases and the ratio of H_2S to SO_2 as related by Equation (5).

$$N_2 = 3.76(SO_2 + 1/2H_2O + O_2) \quad (7)$$

$$H_2S = 2SO_2 \quad (8)$$

The total pressure is expressed by Equation (9).

$$\text{Total pressure} = P = H_2S + SO_2 + S_2 + S_6 + S_8 + H_2O + N_2 \quad (9)$$

Because of the stoichiometry of the system, an oxygen and sulfur balance can be written as the gram atoms of sulfur are equal to the gram atoms of oxygen. In terms of the partial pressure of the constituents and noting that the oxygen content is effectively zero, Equation (10) can be written:

$$H_2S + SO_2 + 2S_2 + 6S_6 + 8S_8 = 2SO_2 + H_2O \quad (10)$$

The complete reaction equilibria can be calculated by evaluating the equilibrium constants as a function of temperature for Equations (2), (3) and (5) and solving them simultaneously with the system boundary conditions of (7), (8), (9) and (10). A unique and relatively simple method of calculation is presented which of necessity is a trial-and-error procedure. The equilibrium constants of interest are

$$K_2 = \frac{(S_2)^2}{S_6}$$

$$K_3 = \frac{(S_2)^4}{S_8}$$

$$K_5 = \frac{(H_2O)^2(S_2)^{3/2}}{(H_2S)^2(SO_2)}$$

Equations (7), (8) and (9) may be combined to give,

$$P = 6.76SO_2 + S_2 + S_6 + S_8 + 2.88H_2O \quad (11)$$

Equations (8) and (10) yield,

$$SO_2 + 2S_2 + 6S_6 + 8S_8 = H_2O \quad (12)$$

Equations (5) and (8) yield,

$$K_5 = \frac{(H_2O)^2}{4(SO_2)^3}(S_2)^{3/2} \quad (13)$$

Because of the low total pressures involved, not exceeding about 2 atm. in commercial sulfur-recovery systems, the assumption is made that fugacities are equal to partial pressures and that the system follows the ideal gas laws.

The calculation procedure involved the following steps.

1. Assume the ratio of $\frac{(H_2O)^2}{(SO_2)^3}$ as A.
2. From Equation (13) calculate the partial pressure of S_2.
3. From Equation (2) calculate the partial pressure of S_6.
4. From Equation (3) calculate the partial pressure of S_8.
5. Solve Equations (11) and (12) simultaneously for the partial pressures of H_2O and SO_2.
6. From step (5) calculate the ratio of $\frac{(H_2O)^2}{(SO_2)^3}$ and compare with that assumed in step (1). Repeat the procedure until the assumed value equals the calculated value of A.

Certain simplifying techniques may be employed in making this calculation which results in the necessity for not more than three and usually only two approximations. By inspection, an approximate value of A can usually be chosen which is within 0.05 to 20 times

the true A value. The ratio of the assumed to calculated A derived by the above procedure is plotted against the diatomic sulfur partial pressure, for example, on semilog coordinates. The nature of the resulting curve is substantially straight with little curvature and results in approximately a uniform slope for various pressures at constant temperature. The correct value of S_2 may be read from this curve and the complete composition analysis calculated.

Table 1 summarizes the free-energy changes for reactions (1), (2), (3) and (5) evaluated as a function of temperature from the data of Kelley (*11*) for the thermodynamic properties of sulfur compounds and the data of the National Bureau of Standards for the free energy of formation of water vapor. The corresponding equilibrium constants are given in Table 2.

In pursuance of the method of calculation just outlined, a series of curves was developed for the sulfur yield as a function of both temperature and pressure. The per cent conversion was defined in terms of the equilibrium partial pressures as,

$$\% \text{ conversion} = \frac{2S_2 + 6S_6 + 8S_8}{2S_2 + 6S_6 + 8S_8 + H_2S + SO_2} \times 100 \qquad (14)$$

These values are plotted in Figure 5 and the pertinent calculated values summarized in Tables 3 and 4.

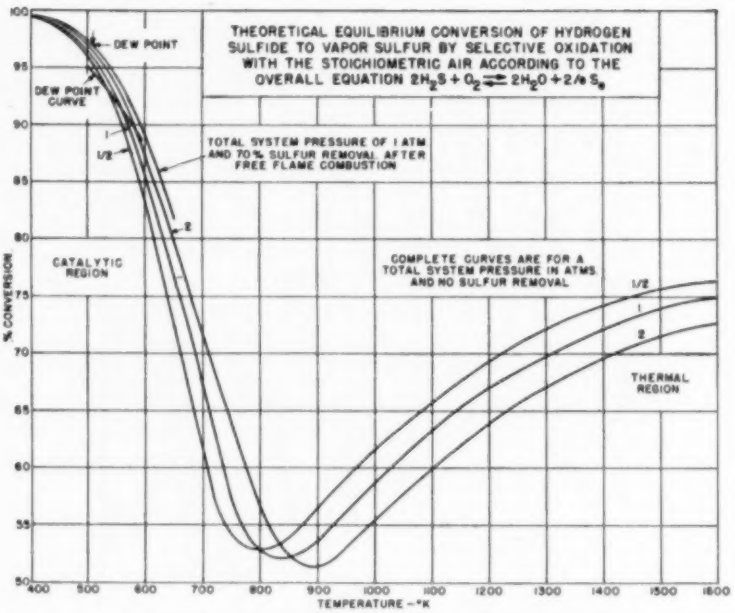


Fig. 5. Theoretical equilibrium conversion of hydrogen sulfide to vapor sulfur by selective-oxidation with the stoichiometric air according to the over-all equation $2H_2S + O_2 \rightleftharpoons 2H_2O + 2/8S_8$.

Noteworthy is the fact that the conversion to elemental sulfur passes through a minimum value in the region of 800-900° K. for the pressure range of ½ to 2 atm. which effectively covers the pressures encountered in modern industrial practice. Two regions may be defined corresponding to approximately the areas on each side of the minimum point in the conversion curve. The low-temperature area with yields approaching 100% can be characterized as the catalytic region because the presence of a catalyst is required to cause reaction to take place between the hydrogen sulfide and sulfur dioxide. At temperatures above the minimum and particularly above about 1300° K., the reaction kinetics in free-flame combustion is rapid enough to achieve the maximum yield compatible with the thermodynamics of the particular system involved. The minimum in the equilibrium-conversion curve is caused by the shift in the predominant sulfur specie with temperature. The formation of diatomic sulfur by reactions (1) and (5) increases with increasing temperature; whereas, the opposite is true with S_6 and S_8. The shift in the predominant form of sulfur specie also accounts for the reversal of the effect of total system pressure with temperature. At constant temperature in the thermal region, conversion decreases with increase in pressure because of the presence predominantly of S_2 and the formation of a greater number of moles in the products of reaction. In the catalytic region, the pressure effect reverses itself because of the large presence of S_6 and S_8 and the formation of fewer moles in the reaction mixture.

One of the key considerations in the design of sulfur-recovery systems, is operation of the catalytic reactors at as low a temperature as possible that is still above the sulfur dew point. The latter can be looked upon as the minimum operating temperature. In Figure 6 and Table 4 are summarized the sulfur par-

Table 1.—Free Energy Changes in Gram Calories Per Formula

	Temp. °K.								
REACTION	400	600	800	900	1000	1100	1200	1600	2000
1	−73,908	−73,315	−72,911	−72,634	−72,360	−72,080	−71,805	−70,567	−69,146
2	36,815	22,196	7,310	−203	− 7,750	−15,370	−23,016	−53,883	−85,157
3	53,532	31,225	8,518	− 2,940	−14,480	−26,069	−37,727	−84,784	−132,450
5	5,793	2,958	−93	− 1,547	− 3,000	− 4,459	− 5,917	−11,598	−17,057

Table 2.—Equilibrium Constants = Kp

	Temp. °K.								
REACTION	400	600	800	900	1000	1100	1200	1600	2000
2	7.71×10^{-21}	8.24×10^{-9}	1.007×10^{-2}	1.12	49.3	11.32	15,520		
3	5.67×10^{-30}	4.24×10^{-12}	4.71×10^{-5}	5.17	1444	1.55×10^{3}	7.25×10^{6}		
5	6.84×10^{-4}	8.37×10^{-2}	1.06	2.38	4.53	7.69	11.96	38.4	73.1

Table 3.—Calculated Equilibrium Compositions in Partial Pressures (atm.)

Total Pressure = ½ Atm.

Component	Temp. °K. 600	800	900	1000	1600
S_2	.0004	.0310	.0424	.0465	.0572
S_6	.0105	.0030	.0001	0	0
S_8	.0090	.0002	0	0	0
SO_2	.0093	.0242	.0219	.0192	.0118
H_2S	.0186	.0484	.0438	.0385	.0236
H_2O	.1448	.1058	.1073	.1122	.1261
N_2	.3074	.2880	.2845	.2836	.2813
% Con.	83.0	52.9	56.6	61.7	76.4

Total Pressure = 1 Atm.

Component	Temp. °K. 400	600	800	900	1000	1600
S_2	0	.0005	.0470	.0900	.0888	.1123
S_6	.0014	.0197	.0103	.0005	.0001	0
S_8	.0402	.0207	.0010	0	0	0
SO_2	.0005	.0143	.0488	.0466	.0413	.0250
H_2S	.0010	.0286	.0976	.0932	.0826	.0500
H_2O	.3228	.2992	.2126	.2095	.2194	.2496
N_2	.6351	.6170	.5827	.5702	.5678	.5631
% Con.	99.55	86.8	52.8	53.7	59.0	75.0

Total Pressure = 2 Atm.

Component	Temp. °K. 600	800	900	1000	1600
S_2	.00066	.0676	.1475	.1683	.2184
S_6	.0354	.0306	.0029	.0001	0
S_8	.0456	.0044	.0001	0	0
SO_2	.0259	.0911	.0983	.0892	.0543
H_2S	.0518	.1822	.1966	.1784	.1086
H_2O	.6044	.4451	.4115	.4264	.4913
N_2	1.2362	1.1790	1.1434	1.1376	1.1274
% Conv.	87.0	56.4	51.4	55.8	72.6

tial pressures as a function of system pressure and temperature. The vapor pressure of sulfur is also plotted in Figure 6 and the intersection of this curve with the sulfur partial-pressure curves corresponds to the dew points. The dew-point curve is superimposed on the conversion curves of Figure 5. It is significant that along an isotherm, the yield is favored with increasing pressure, but the catalytic case can be operated at lower temperatures with lower total pressures giving an effective higher yield. Thus the maximum yield with one catalyst case and no sulfur removal is increased by 4% in going from 2 to ½ atm. In contrast to this, at the dew point for 2 atm. total pressure of 580° K., the theoretical yield is about 4% higher than for ½ atm. and the same temperature. The theoretical dew points and yields are summarized in Table 5.

Where a pure hydrogen sulfide gas feed exists or where it is required to minimize the output of sulfur-bearing gases into the atmosphere because of air-pollution control, sulfur is frequently removed in a primary condenser following the boiler. With this type of operation the sulfur recovery follows a different curve at constant pressure from that previously developed. It has been observed in the laboratory and plant that sulfur yields equal to about 70% can be obtained after free-flame combustion. Assuming such a yield, the theoretical sulfur recovery in the catalytic region can be calculated by setting up the proper boundary conditions. Equations (7), (8) and (9) are still valid. However, the sulfur and oxygen balance is now written as,

$$\text{gram atoms sulfur} = 0.3\ (\text{gram atoms oxygen})$$

or,

$$H_2S + SO_2 + 2S_2 + 6S_6 + 8S_8 = 0.6SO_2 + 0.3H_2O \qquad (15)$$

Equation (12) then becomes,

$$8SO_2 + 6.667S_2 + 20S_6 + 26.667S_8 = H_2O \qquad (16)$$

With these new expressions, the identical calculation procedure previously outlined is followed. Similar conditional equations may be written for the presence of water vapor, tail gas recycle, etc., and new conversion curves calculated. For the case chosen the yield has been evaluated and is summarized in Table 6. Data are plotted in Figures 5 and 6 as well. The maximum theoretical yield thus obtained when operating at the dew point is 97.1% or about 5% greater than without the primary condenser.

The technique described to calculate the true sulfur equilibria is completely general. One common attempt to simplify the procedure has been discussed in the past which is predicated upon treating the complex sulfur equilibria as a single specie of average molecular weight corresponding to the true equilibria mixture. The inherent error in this method has not been recognized, and it is accordingly reviewed. The over-all reaction is considered as taking place between H_2S and SO_2, and reactions (2), (3) and (5) are combined into one omnibus equation as,

$$2H_2S + SO_2 \rightleftharpoons xS_e + 2H_2O \qquad (17)$$

$$xS_e = aS_2 + bS_6 + cS_8 \qquad (18)$$

$$x = a + b + c \qquad (19)$$

$$e = 3/x = y_2(2) + y_6(6) + y_8(8) \qquad (20)$$

where

$$y_2 + y_6 + y_8 = 1 \qquad (21)$$

The mole fractions, y_i, are evaluated at a given temperature and total sulfur

Table 4.—Total Sulfur Pressure in Atmospheres When No Sulfur Is Removed

Temp.—° K.	Total System Pressure—Atm. ½	1	2
1600	.0572	.1123	.2184
1000	.0463	.0889	.1684
900	.0425	.0805	.1504
800	.0342	.0583	.1026
600	.0199	.0409	.0816
400	.0208	.0416	.0832

pressure. The actual moles are a, b and c formed of S_2, S_6 and S_8, respectively, at equilibrium. The free-energy change for Equation (17) can be evaluated by conventional means remembering to use the equilibrium moles as defined by Equation (18). Unfortunately the free-energy change becomes a function of both temperature and the equilibrium total sulfur pressure. The hybrid equilibrium constant for Equation (17) is written as

$$K_{17} = \frac{(S_e)^x(H_2O)^2}{(H_2S)^2(SO_2)} \qquad (22)$$

or,

$$K_{17} = A(S_e)^x \qquad (23)$$

where

$$A = \frac{(H_2O)^2}{(H_2S)^2(SO_2)}$$

Because of the method of calculating the free-energy change which is thermodynamically correct, the valid expression for K_{17} is,

$$K_{17} = A(S_2)^a(S_6)^b(S_8)^c \qquad (24)$$

where all values are expressed in partial pressures. Accordingly, if Equations (22) and (23) are thermodynamically sound,

$$(S_e)^x = (S_2)^a(S_6)^b(S_8)^c \qquad (25))$$

By Equation (19),

$$S_e = (S_2)^{y_2}(S_6)^{y_6}(S_8)^{y_8}$$

(which is impossible) (26)

However, the true equilibrium sulfur partial pressure is given by,

$$S_e = S_2 + S_6 + S_8 \qquad (27)$$

Thus if Equation (22) is used to calculate the equilibrium sulfur partial pressure, errors in the total pressure as well as errors in the % conversion, dew points, other compound compositions and secondary design calculations will result unless only one molecular specie exists. However, when the latter is true, straightforward calculation procedures may be used.

High-Temperature Combustion

For the conversion of a highly concentrated hydrogen sulfide stream, the free-flame-combustion process described in the Baehr and Braus patent appears particularly attractive as the first stage in the process. Such a process should decrease the load on the catalytic-conversion step from the kinetic as well as the thermochemical point of view. The use of the free-flame combustion is also desirable from another point of view. The presence of a small proportion of aromatic or aliphatic hydrocarbons in the hydrogen sulfide stream was found to cause a continuous deactivation of bauxite catalyst by coke deposition. Attempts to add the stoichiometric proportion of air necessary for complete combustion of the hydrocarbons as well as the conversion of hydrogen sulfide to sulfur at temperatures up to 460° C. were unsuccessful. The result was an increased rate of catalyst deactivation as well as increased formation of SO_2 at the expense of sulfur owing to the accelerating effect of oxygen on the dehydrogenating condensation to coke. Thus, by effecting the complete combustion of hydrocarbons, the free-flame combustion also serves to protect the catalyst from deactivation.

Table 5.—Theoretical Dew Points and Corresponding Yields

Total System Pressure Atm.		No S Removal	Theoretical Dew Point, °K.	Theoretical Yield at Dew Point, %
½	—	"	527	93.5
1	—	"	553	92.0
2	—	"	580	89.7
1	—	70% S removal	508	97.1

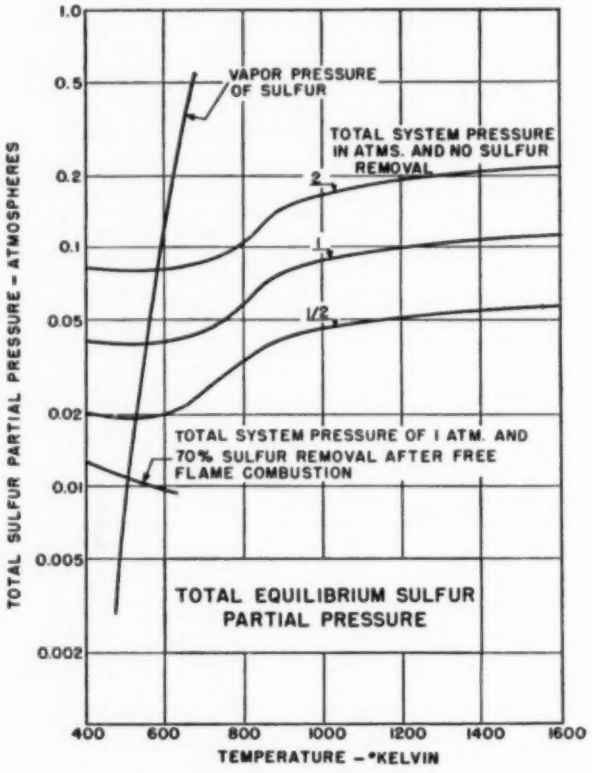


Fig. 6. Total equilibrium sulfur partial pressure.

Table 6.—Sulfur Yield for 70% Sulfur Removal and One Atm. Pressure

Temp. °K	Total Conversion
400	99.6
450	98.9
500	97.2
550	94.0
600	88.9
650	81.5

Since the theoretical equilibrium calculations confirmed the possibility of high conversions to sulfur, it was decided to investigate the possibilities of the free-flame combustion. The theoretical flame temperature for the combustion of pure hydrogen sulfide with the stoichiometric proportion of air to produce sulfur was calculated by standard procedures to be of the order of 1400° C. According to the theoretical equilibrium calculations, a maximum conversion to sulfur of about 75% can be expected at these temperatures and standard operating pressures. Furthermore, at such temperatures, the kinetics of the reactions were expected to be rapid enough that equilibrium would be achieved.

In the laboratory, a preliminary investigation of the free-flame combustion of pure hydrogen

sulfide was carried out using small Pyrex glass burners. The burners comprised simply two concentric tubes. The inner tube carried the air while the H_2S was conveyed through the annular space so that mixing occurred in the flame periphery. The combustion, of course, was carried out in an enclosed space so that the fuel air ratio would be controlled.

Flame stability with such burners was relatively easily achieved by proper adjustment of the linear velocities of the reactants, the burner diameter and the flame temperature. At low linear velocities, the flame was stable even when the surroundings were at room temperature. To maintain flame stability at higher linear velocities, it was necessary to minimize radiation heat losses by providing a heated environment. In commercial operation, of course, the combustion is carried out in a well-insulated combustion chamber.

According to the data in the literature, the yield of sulfur from the noncatalytic combustion of hydrogen sulfide varies from 60 to 90% depending on the conditions. When the combustion was carried out in a heated reaction tube where mixing of the reactants occurred throughout the reaction zone, as reported by Herndon, et al. (*10*), sulfur yields varied from 76 and 82% between 600 to 750° C. Packing the reaction zone with tabular alumina granules did not appear to affect the results.

Baehr and Braus (*1*) claim yields of 80-90% when the combustion is carried out in a free flame at temperatures up to 1000° C. In both cases, the yields claimed are in excess of that predicted by the calculated thermodynamic equilibria.

In experiments with free-flame combustion at temperatures in excess of 1300° C. followed by proper and critical quench rates in the Great Lakes Carbon Corp. laboratories, improved results were obtained (*8*).

The apparatus comprised a 10-mm. Pyrex tube concentric to a 6-mm. Pyrex tube. The inner tube carried the air while the H_2S passed through the annular space to the flame. After the burner was ignited and set in place, the flame was allowed to heat the glass enclosure to a temperature just above 100° C. so that water would not condense out and serve as a medium for further reaction. After the system was well purged with reaction products, the off-gases were passed through an analytical aqueous sodium hydroxide scrubber. The sulfur yield was calculated as the difference between the amount of H_2S charged and the unreacted H_2S and SO_2. With flow rates of 0.31 cu.ft./hr. of H_2S and 0.76 cu.ft./hr. of air and proper quench rates, the average yield of sulfur in many experiments was $90 \pm 1\%$. These yields are greater than the calculated equilibrium. The experimental method appears to have been sufficiently precise. The analytical method gave satisfactory results with known mixtures of hydrogen sulfide and sulfur dioxide in nitrogen. Care was taken to preclude the further reaction of product hydrogen sulfide and sulfur dioxide in condensed water which would give high apparent sulfur yields.

Yields greater than the theoretical equilibrium at the flame temperature would be obtained if reaction continued during cooling until the equilibrium was frozen at a temperature where the reaction rates become slow. However, this seemed unlikely since the actual conversion corresponds to the equilibrium at a temperature of 300° C. so that the reaction rates would have to be extremely rapid down to that temperature. Furthermore, Taylor and Wesley (*14*) have shown that the reaction occurs principally on surfaces below 730° C. Since the surface to volume ratio in the flame enclosure was quite small, it is improbable that such a mechanism is in operation.

A more plausible explanation lies in the fact that owing to kinetic restrictions, the upper limit of the conversion may be controlled by the thermodynamic equilibrium of the primary reaction,

$$2H_2S + O_2 \rightarrow 2H_2O + S_2$$

rather than the calculated equilibrium involving sulfur dioxide. The equilibrium constant for the above reaction is on the order of 10^{10} at 1300° C. so that the conversion could be considerably more than 90%. This would occur if the formation of sulfur dioxide is suppressed kinetically. The kinetics of the oxidation of hydrogen sulfide is undoubtedly quite complex and like other oxidations probably occurs by a free radical mechanism. Although little is known of the detailed mechanism, it seems probable that sulfur is formed before sulfur dioxide in the chain of reactions especially at high temperatures. The sulfur dioxide may actually be formed principally from the sulfur produced. Then, as suggested by Herndon, et al. (*10*), a competition for the oxygen is set up between the unreacted hydrogen sulfide and the product sulfur.

In such a sequence of reactions, it is easy to understand how sulfur might be produced as the principal product. The rate of formation of sulfur dioxide is necessarily slower than that of sulfur since it is a function of the partial pressure of hydrogen sulfide, sulfur and oxygen, and as the partial pressure of sulfur is increasing, that of the oxgyen is decreasing. Furthermore, the suppression of the formation of sulfur dioxide is also favored by the rapid quench in accordance with the Gamson (*8*) process. The formation of sulfur dioxide by the interaction of the products, sulfur and water, would be expected to be relatively slow because of the complexity of the stoichiometry. Such secondary reactions are further suppressed by the rapid quench to low temperatures which occurred in the Great Lakes Carbon free-flame experiment.

Catalytic Studies

For the purposes of the experimental investigation of the catalytic conversion as the second stage in the process, it was assumed that the calculated equilibrium conversion to sulfur was attained in the high-temperature combustion stage. At a combustion temperature of 1280° K., it was calculated that conversion was 69.4% and that this quantity would be removed before the stream entered the catalytic chamber.

Most commercial hydrogen sulfide streams contain appreciable quantities of carbon dioxide and light hydrocarbons. It has been established that the high-temperature combustion of such a gas results in the conversion of part of these carbon compounds to carbonyl sulfide. Therefore, the effluent from the combustion unit will comprise sulfur, nitrogen, steam, sulfur dioxide, carbonyl sulfide and unreacted hydrogen sulfide. If the combustion is carried out with the proper proportion of air, the effluent will contain the stoichiometric quantity of sulfur dioxide necessary to convert all the carbonyl sulfide and hydrogen sulfide to sulfur according to the following equations:

$$2H_2S + SO_2 \rightarrow 3S + 2H_2O$$

$$2COS + SO_2 \rightarrow 3S + 2CO_2$$

The catalyst used in the final stage of the recovery process must, therefore, promote both of these reactions efficiently. Accordingly, the catalytic activity of commercial bauxite was determined for each of these reactions separately as well as for the oxidation of CS_2. Bauxite is suggested in the literature (*5, 8*) as being efficient for the COS and CS_2 conversions with SO_2.

The catalytic reactor (Fig. 7) comprised a 1½-in. I.D. sillimanite tube, 36 in. long, heated electrically by means of nichrome resistance wire. The catalyst bed occupied the middle 18 in. Reactant gases were introduced by means of pressure regulators and flowmeters. Water was introduced by saturating nitrogen with water vapor at a controlled temperature. The sulfur condenser and reservoir as well as the outlet lines were maintained at the melting point of sulfur to keep water from condensing out and serving as a solvent for further reaction between SO_2 and H_2S. The catalyst used was 4-8 mesh Porocel, which is an activated bauxite with low-iron content and 2% volatile content.

In a typical experiment, the catalyst was charged and the reactor brought to 250-300° C. When the temperature had become relatively constant, the reactants were introduced and flow rates adjusted. The reaction was allowed to proceed for at least fifteen minutes to purge the system with reaction products. As soon after this as the temperatures were lined out, the off-gases were switched to an analytical scrubber for a definite time interval. The liquid sulfur was weighed and the yield of unreacted H_2S +

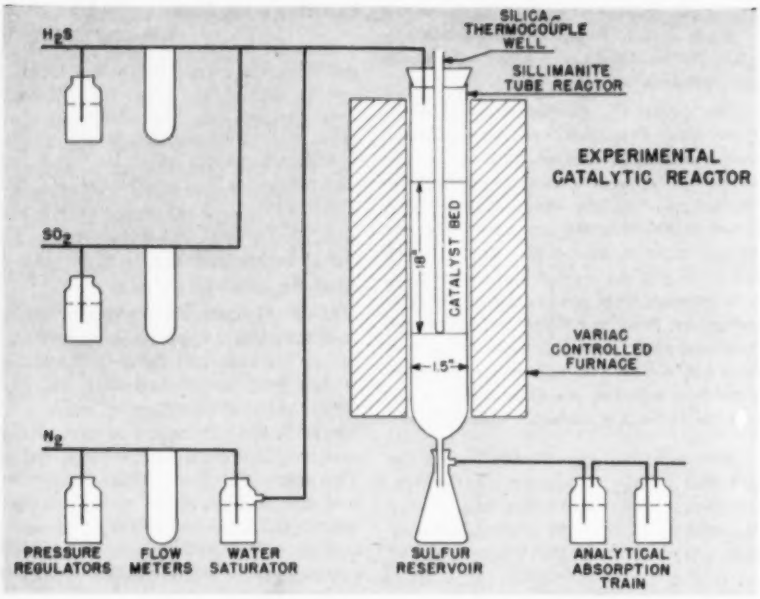


Fig. 7. Experimental catalytic reactor.

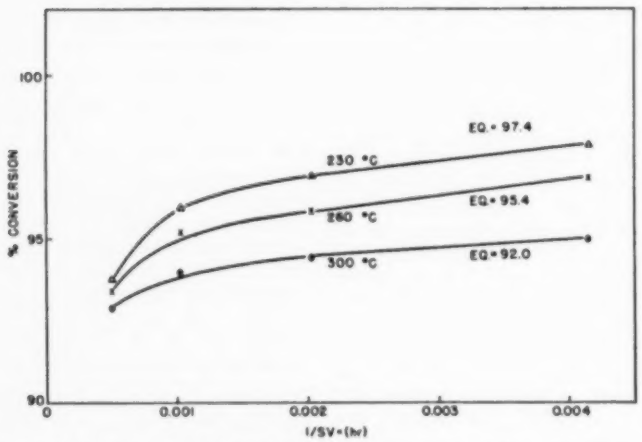


Fig. 8. Over-all sulfur yield at 1 atm. total pressure and 69.4% sulfur removal after free-flame combustion.

Table 7.—Over-all Sulfur Yield at One Atm. Total Pressure and 69.4% Sulfur Removal After Free-Flame Combustion

Space Velocity Std. cu. ft. gas/(cu.ft.cat.)(hr.)	Temp. °C.	Total Conversion
240	230	97.9
240	260	96.7
240	300	94.8
480	230	96.9
480	260	95.8
480	300	94.4
960	230	96.0
960	260	95.2
960	300	94.0
1920	230	93.8
1920	260	93.4
1920	300	92.9

SO_2 determined analytically. The method of analysis used was to absorb the unreacted H_2S and SO_2 in concentrated NH_4OH. The total sulfur-bearing gases were determined by iodiometric titration on one aliquot of the sample; on another aliquot the H_2S was precipitated with excess silver nitrate, filtered off and the unused $AgNO_3$ back titrated with potassium thiocyanate. The composition of the reactant gas was essentially that of the effluent of the noncatalytic combustion of pure hydrogen sulfide (assuming a 69.4% conversion to sulfur) after having been cooled to condense out all the sulfur. Its exact analysis is shown in Table A.

Table A.—Mole %

H_2S	6.78
SO_2	3.39
N_2	63.00
H_2O	26.83

Figure 8 and Table 7 present the yield of sulfur for the over-all process (high-temperature combustion followed by the catalytic reaction) as a function of the reciprocal space velocity (hr.) and temperature of the catalytic reaction. These yields were calculated from the experimental data assuming a 69.4% conversion to sulfur in the high-temperature combustion. As the space velocity decreases, the curves appear to be approaching asymptotically an equilibrium value. At the right of each curve is shown the calculated equilibrium conversion at that temperature. These values take into account the displacement of the equilibrium, resulting from the removal of the sulfur from the effluent, from the combustion by condensation prior to introduction to the catalytic reactor.

The agreement between the calculated equilibria and the experimentally determined values at a space velocity of 240 is quite close. However, the experimental results are somewhat higher than the theoretical values. Table 8 summarizes the extrapolated experimental curves of Figure 8 at zero space velocity which is the ultimate conversion at constant temperature. The difference between these and the calculated values are plotted as a function of temperature in Figure 9. This difference between the theoretical and experimental results is probably due to slight inaccuracies in the basic data of Preuner & Schupp. Figure 9 can be looked upon as a first approximation correction factor to the theoretical curve in the temperature range covered.

It was found that the catalytic reaction must be carried out at a temperature above that at which liquid sulfur condenses out of the reaction mixture, since liquid sulfur effectively poisons the activity of the catalyst. In this study, the initial condensation of sulfur from the reaction mixture occurred at about 250° C. However, apparently reliable yield data were obtained below the dew point at the lower space velocities by the following procedure:

The reaction was carried out at a temperature well above 250° C. to purge the system with reaction products and condition the catalyst. Then the reactants were shut off and the catalyst bed allowed to cool to a temperature below 250° C. The reaction gases were introduced again and as soon as the temperature became constant (about 5 min.) the analysis was taken. At space velocities below 500, the analyses could be obtained before the poisoning became appreciable. Thus, the data obtained below 250° tend to be a conservative estimate of the conversions obtainable at those temperatures.

For the experimental investigation of the conversion of carbonyl sulfide to sulfur by oxidation with sulfur dioxide, the apparatus, procedure and catalyst used were the same as those just described for the hydrogen sulfide-sulfur dioxide

reaction. The reactant gas comprised a blend of carbonyl sulfide, sulfur dioxide and nitrogen in the concentrations which would be expected in the effluent from the combustion unit. The exact analysis was as shown in Table 8.

Table 8.—Vol. %

COS	5.5
SO_2	2.75
N_2	91.75

The off-gases from the reactor were scrubbed free of sulfur dioxide with aqueous sodium hydroxide and then the carbonyl sulfide absorbed in alcoholic sodium hydroxide. These solutions were analyzed, the sulfur weighed, and the yield of sulfur calculated as the difference between the moles of sulfur charged and recovered in the off-gases.

Table 8.—Per Cent Difference Between Extrapolated Experimental Ultimate Yield and Theoretical Calculated Yield at One Atm.—Total Pressure and 69.4% Sulfur Removal After Free-Flame Combustion

Temp. °C.	% Ultimate Yield	% Theoretical Yield	Δ Ultimate-Theoretical
300	95.2	92.0	3.2
260	97.4	95.4	2.0
230	98.3	97.4	0.9

Table 9.—Per Cent of Reduction Carbonyl Sulfide to Sulfur Over a Bauxite Catalyst

Run No.	Space Velocity std.cu.ft./(cu.ft.)(hr.)	Temp. °C.	% Sulfur Yield
10	200	272	93.5
11	↓	262	95.1
12	↓	303	97.2
13	↓	222	65.3
14	↓	280	93.0
15	↓	248	57.0
16	↓	278	93.5

Five runs were made at a space velocity of 200 and various temperatures between 255° C. and 303° C. The yield of sulfur appeared to be relatively constant over this range, the average being 94.5 ± 2%. The data below 250° C., which is the approximate dew point of the product mixture, are not too accurate. However, it appeared that the conversion decreases rapidly below 255° C. to approximately 65% at 220° C. This is shown in Figure 9 and Table 9.

Commercial Processes

It is clear from the theoretical analysis just presented that the reaction must be carried out, at least in its final stages, at temperatures below 300° C. in order to achieve yields of 95% or better. In achieving this in a practical process design, two important factors must be taken into account. They are:

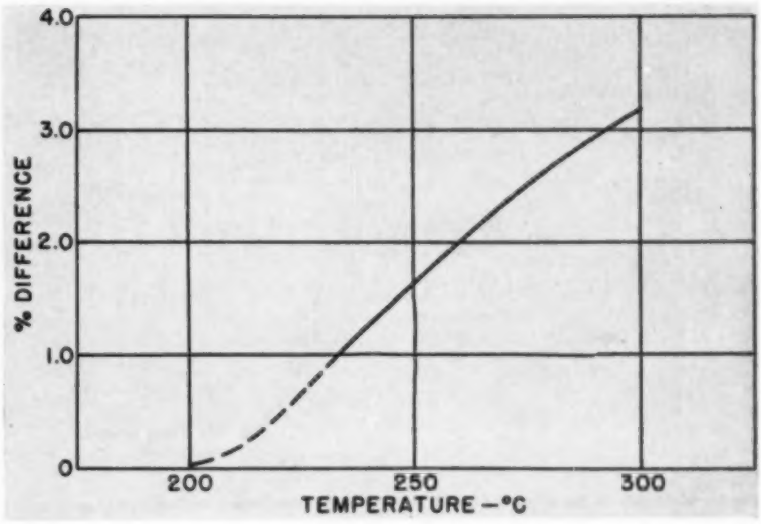


Fig. 9. Per cent difference between extrapolated experimental ultimate yield and calculated theoretical yield at 1 atm. total pressure and 69.4% sulfur removed after free-flame combustion.

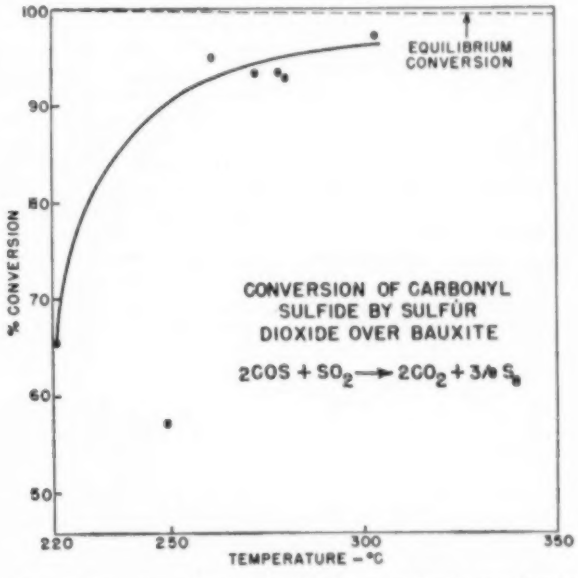


Fig. 10. Conversion of carbonyl sulfide by sulfur dioxide over bauxite.

1. The exothermic heat of reaction. The greater the amount of reaction taking place in a single unit, the more difficult it is to balance reaction heat with heat removal at a sufficiently low temperature. It is necessary, therefore, that the recovery of sulfur from concentrated streams of hydrogen sulfide be carried out in at least two stages, the last of which must be catalytic in nature to achieve conversion at temperatures below 300° C.

2. The sulfur dew point of the reaction product. The catalytic reaction must be carried out at a temperature greater than that at which sulfur begins to condense out in liquid form since the latter effectively poisons the activity of the catalyst. In the system where the reactants are pure hydrogen sulfide and air, liquid sulfur will condense out at the equilibrium conversion of about 92% at 280° C. and 1 atm. total pressure. Thus it is desirable that a substantial portion of the total conversion to sulfur be effected and the sulfur condensed out before the final catalytic stage.

To illustrate the effect of these conditions on process design, the evolution of the Claus process

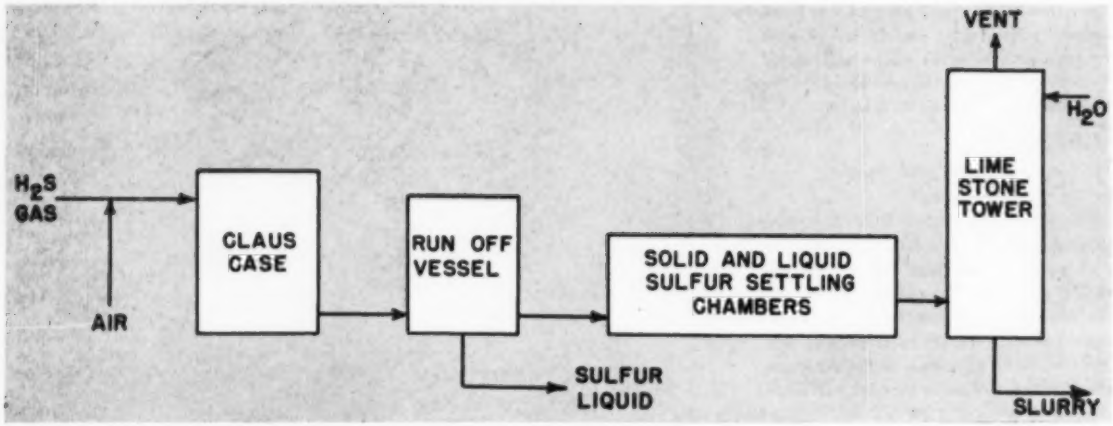


Fig. 11. Claus process.

may be examined. In the original Claus process (Fig. 11), the entire reaction was carried out in a single catalytic converter. Owing to the restriction imposed by the exothermic heat of reaction, the space velocity was limited to about 2-3 vol. of hydrogen sulfide (S.T.P.)/(hr.)(vol. of cata'yst) at a yield of 70-80% sulfur. In one of the early variations of the Claus process, an attempt was made to correct this difficulty by dilution of the reactants with recycle tail gas (see Fig. 12). Although this resulted in better temperature control, little relief from the basic restriction of the heat reaction on the space velocity was achieved, and much larger units were required to handle the greater gaseous volumes.

The first significant improvement in the process was the I.G. Farbenindustrie modification (Fig. 13). This is a two-stage process in which the hydrogen sulfide stream is split, one third being burned completely to sulfur dioxide under a waste heat boiler, cooled and reacted with the remaining two thirds of the hydrogen sulfide in a bauxite converter. The improvement results from the fact that almost 80% of the total heat of reaction is liberated before the final catalytic conversion. Thus, the restriction imposed by the heat of reaction is removed to a major extent and the space velocity may be increased about one hundred fold. However, because of the sulfur dew point of the mixture, the catalytic reaction temperature is still limited to 280° C. or higher. Only by the addition of a sulfur condenser and a second catalyst converter can the final reaction temperature be lowered. Another advantage of this process is that when large quantities of carbon dioxide are present in the feed, complications in the catalyst case due to the formation of carbonyl sulfide in the combustion chamber are negligible unless hydrocarbons are present also in the feed.

In the later I. G. Farbenindustrie modification (Fig. 14), the whole hydrogen sulfide stream is burned with the stoichiometric proportion of air necessary for conversion to sulfur in a free flame. This unit, where 60-70% of the total conversion to sulfur takes place, was followed by one or more catalytic converters. The improvement of this process over the previous modification is twofold:

1. Of the total heat of reaction 90-95% is liberated prior to the final catalytic-conversion stage, and,

2. At least 70% of the total conversion to sulfur may be effected and the sulfur condensed out prior to the catalytic conversion, thus lowering the maximum dew point of the mixture. For a feed consisting of pure hydrogen sulfide, the maximum dew point would be lowered from about 280° to 235° C. By recycle of tail gases in a ratio of 1:1,

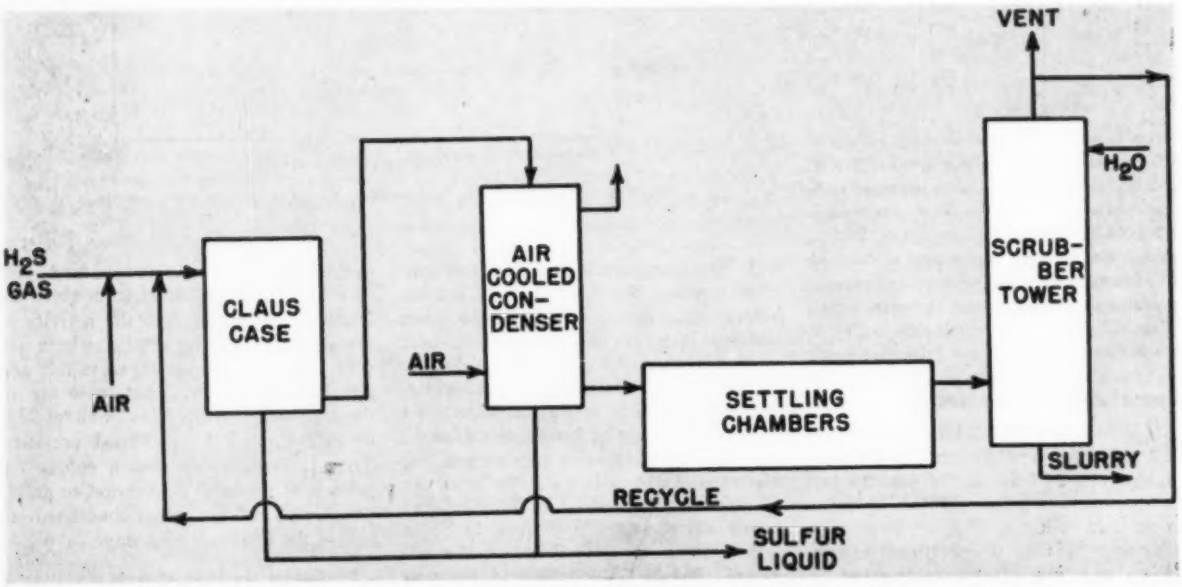


Fig. 12. Modified Claus process.

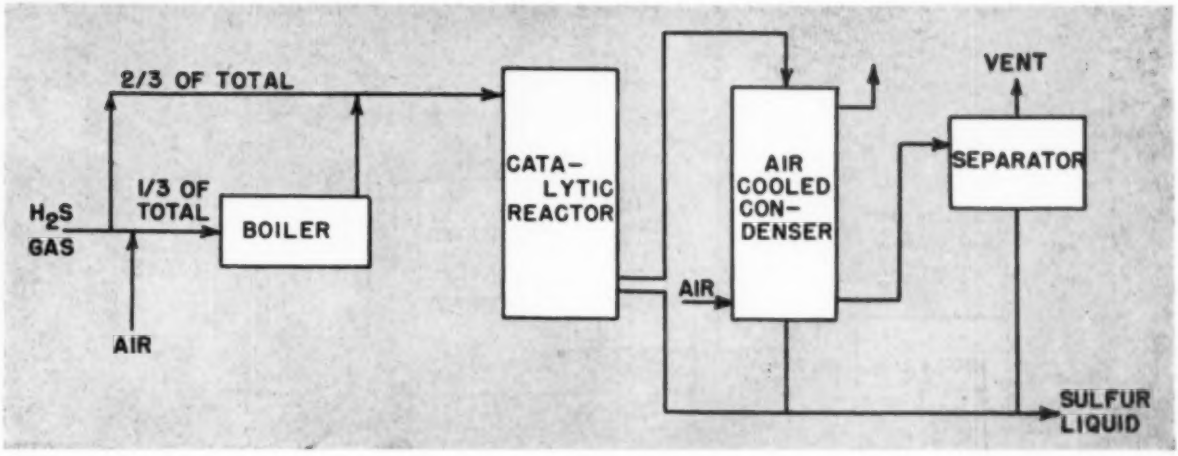


Fig. 13. I. G. Farbenindustrie—Claus process.

the dew point may be lowered even further, permitting reactor temperatures of about 210° C. where sulfur yields in excess of 98% are possible. The lower temperatures outweigh the addition of water. This technique is shown in Figure 15 as the Great Lakes Carbon Corp. process. It is particularly useful where pure hydrogen sulfide streams are encountered and/or air-pollution control necessitates a minimum evolution of sulfur-bearing gases to the atmosphere. Figure 16 summarizes the profile of temperature, dew point and conversion obtained in the process.

Barkholt (*3a*) has patented a process which essentially includes the features of Baehr and Braus (*1*) and Baehr and Mengdehl (*2*) in the presence of appreciable quantities of hydrocarbons. This process operates in the temperature range of 400-500° C. which is allegedly high enough to eliminate carbon deposition on the catalyst.

With the restrictions imposed by the exothermic heat of reaction and the dew point of the mixture effectively removed, the actual yields obtainable will depend only on the activity of the catalyst. In the absence of carbonyl sulfide, bauxite is quite efficient so that conversions as high as 97-98% are obtainable with only one catalytic converter.

The fact that most commercial sources of concentrated hydrogen sulfide are contaminated with small amounts of light hydrocarbons, which are converted to carbonyl sulfide in the high-temperature combustion, complicates the situation. The presence of carbon dioxide likewise affects the formation of carbonyl sulfide. Data presented in this paper indicate that the conversion of carbonyl sulfide is about 93% complete at 260° C. at a total space velocity of 200. Under the same conditions, the conversion of hydrogen sulfide is about 97% complete. On this basis, assuming

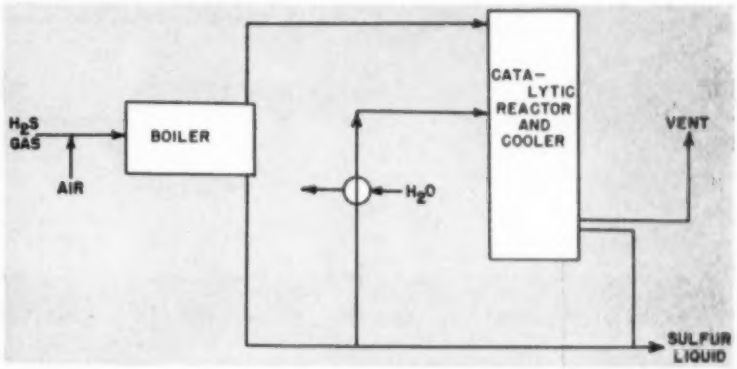


Fig. 14. Modified I. G. F. Claus process.

a conversion of about 70% in the free-flame stage, the over-all yield would approach 97% with only one catalytic converter. However, at space velocities appreciably greater than 200, the conversion of carbonyl sulfide would be incomplete at 260° C. If the temperature is increased to a point where the conversion of carbonyl sulfide is complete, the conversion of hydrogen sulfide becomes incomplete. For this reason, most commercial processes involve two catalytic reactors where COS is present; the first being operated at a temperature level of about 400° C. to assure a high conversion of carbonyl sulfide, and the second reactor operating at as low a temperature as practicable to maintain high conversions of hydrogen sulfide.

The foregoing remarks concerning the restrictions placed on the process design for this reaction by the thermodynamics, the heat of reaction and the dew point of the system apply in particular to concentrated hydrogen sulfide streams. The less concentrated the stream, the less serious are the restrictions. For dilute hydrogen sulfide streams, a single bauxite converter may suffice to accomplish high yields of sulfur by direct oxidation with air. Such a process, shown in Figure 17, has been described by Thompson (*14a*) and Graff (*9*) for simultaneous desulfurization of and sulfur recovery from inflammable gases bearing hydrogen sulfide in low concentrations. In this case, the reactant gases must be preheated. In this process, the concentration of hydrogen sulfide is limited to a relatively low value. For a given operating temperature, and therefore sulfur yield, the space velocity will be an inverse function of the hydrogen sulfide concentration. This fact together with the sulfur dew point limits the concentrations handled practically in this process.

An improved process, especially adapted for simultaneous desulfurization and sulfur recovery, has recently been announced by the Jefferson Lake Sulfur Co. (Fig. 18). The restrictions imposed by the heat of combustion with air are decreased by oxidation with sulfur dioxide over a "novel" catalyst. The sulfur dioxide is obtained by burning a portion of the sulfur product, the heat generated being used for preheating the

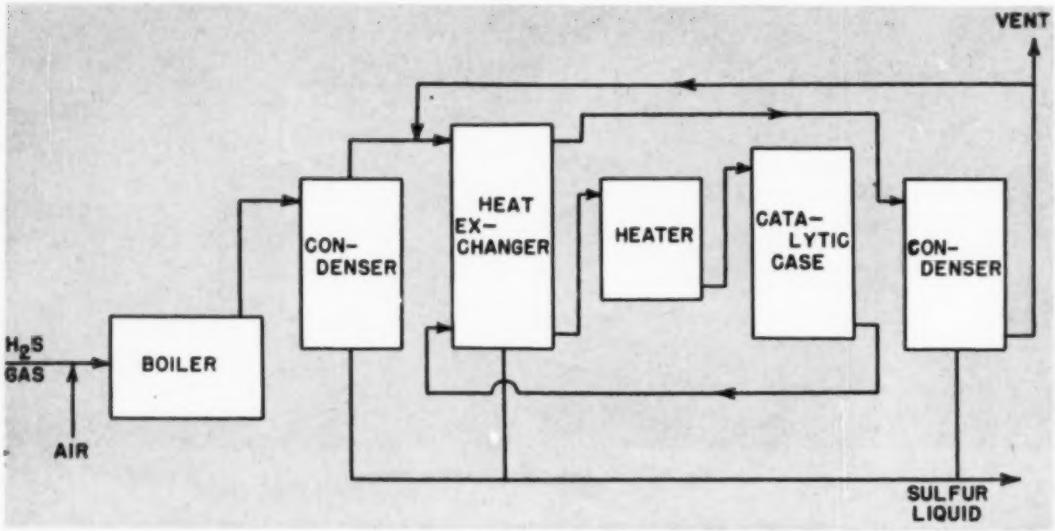


Fig. 15. Great Lakes Carbon Corp. process.

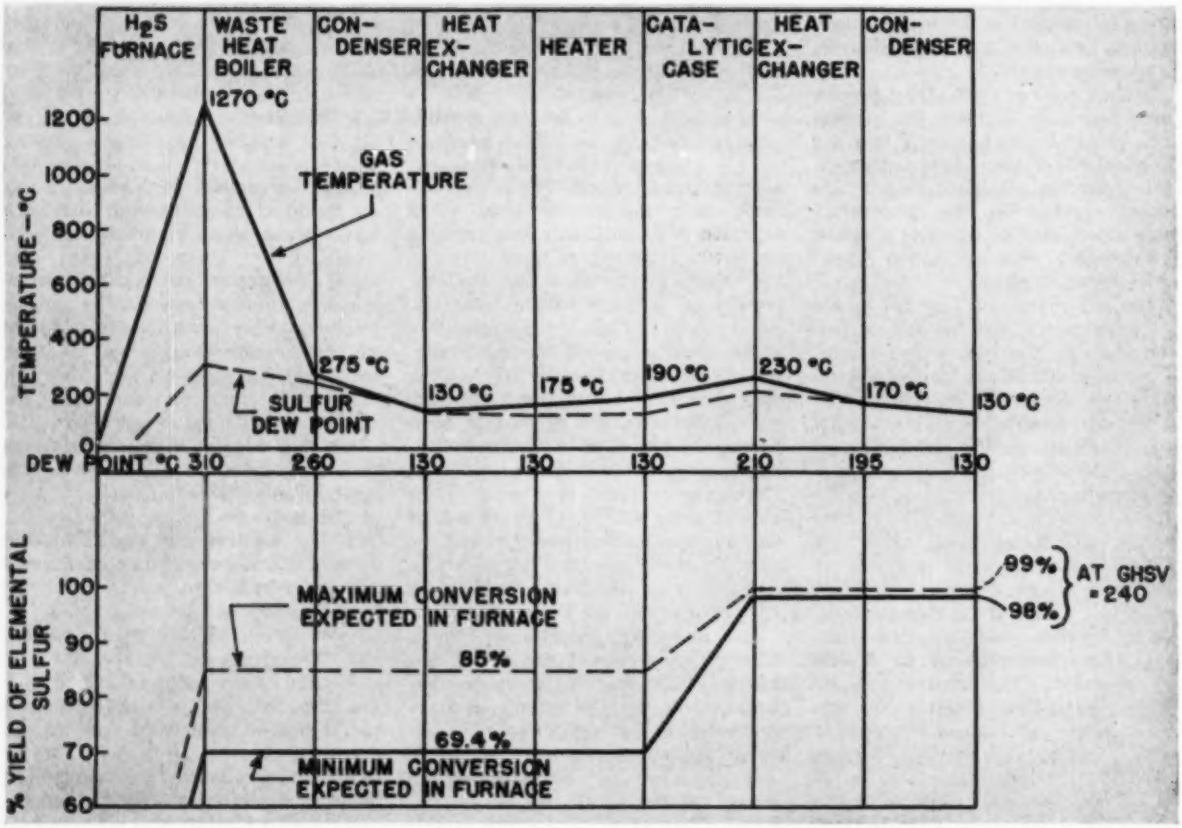


Fig. 16. Profile of temperature; dew point and sulfur conversion in the G.L.C.C. process.

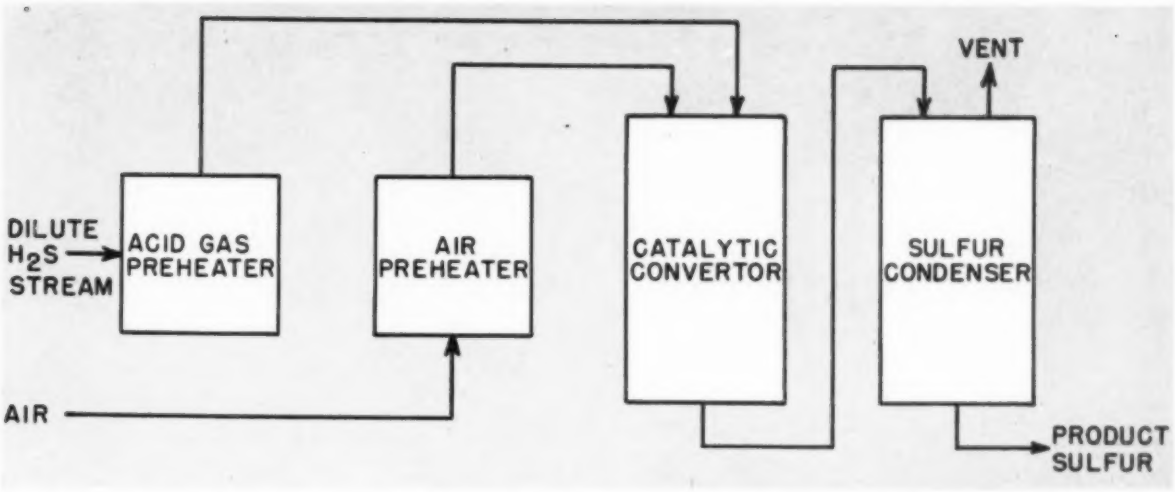


Fig. 17. Jefferson Lake process. Desulfurization of and sulfur recovery from dilute hydrogen sulfide streams.

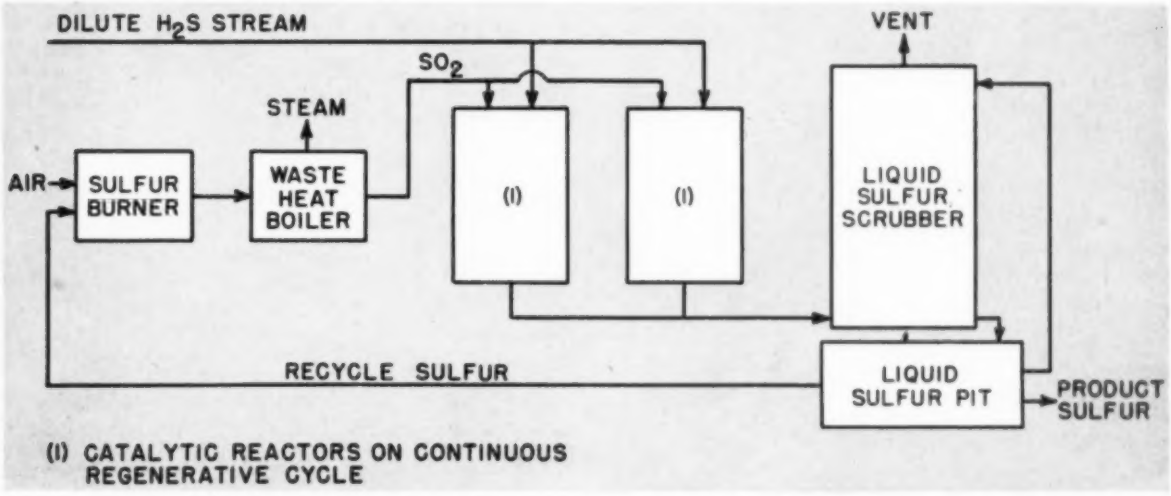


Fig. 18. Jefferson Lake process. Desulfurization of and sulfur recovery from dilute hydrogen sulfide gases.

reactants and the production of steam. Hydrogen sulfide in concentrations from 1-30% can be handled satisfactorily in this manner.

Acknowledgment

The authors wish to express their appreciation to the management of the Great Lakes Carbon Corp. for permission to publish this paper.

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(Presented at the A.I.Ch.E. Kansas City, Mo., Meeting)

Training Scientists Today

George B. Kistiakowsky Harvard University, Cambridge, Massachusetts

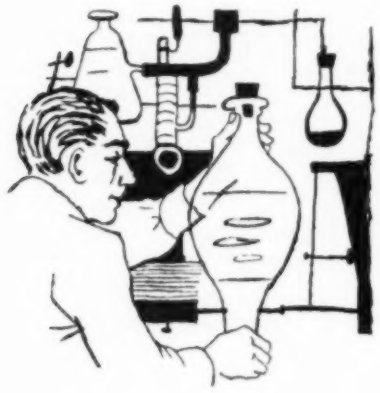
Authoritative voices have been raised in recent years to blame science for most of the present faults of mankind, the terrible destruction of the last wars and the worse one to come with atom and hell bombs. Whether science is indeed the guilty party is a controversial question, but whatever the conclusion, one has to accept science as a potent force in modern civilization. Individually we rely at almost every turn in our daily lives upon objects and procedures which have become available to us through scientific research. On the broader scale we find the entire economic life of this country dependent upon continuing industrial development, built upon a steady stream of practical inventions. But inventions are the fruit of scientific research. And thus the furtherance of a vigorous and creative scientific activity appears to be an indispensable prerequisite to the continuing welfare of this country.

This is a rather old argument, but in recent years it has become reinforced by another and less cheerful one—science has become indispensable to the Military and therefore, in these times of continuing not-so-cold wars, to our national security. Gone are the days when weapons of twenty years ago would serve in battles of today. A major portion of the current rearmament effort is devoted to a search for new weapons based on most recent technological advances. It is therefore not surprising that scientists have become heavily involved in military problems. Whether this is good or bad in itself is not a debate for this paper. But a consequence of this preoccupation is that, unintentionally for the most part, the Military has begun to exercise a profound influence upon the training of young scientists. And unless a total denial is made of the value of pure science, one must become concerned with this matter, lest unhealthy trends prevail.

Over a period of many years in the United States, research in fundamental sciences has become intimately fused with graduate education. Few are the recognized scientists of today whose success was not built upon the work of their graduate students. This is a reversible process, however, because, far better than any formal lecture could, the intimate daily contacts with the research

George B. Kistiakowsky, professor of chemistry, Harvard University, has been for some time engaged in advisory work for the Department of Defense, as a member of the Scientific Advisory Board to the Chief of Staff, U.S.A.F., and the Advisory Committee to the R. and D. Division, Ordnance Department. A native of Russia, Professor Kistiakowsky attended the University of Berlin, Germany, and received in 1925 the Ph. D. degree. Subsequently he became International Education Board Fellow in Princeton, N. J. and later a staff member of chemistry department, Princeton University. In 1930 Professor Kistiakowsky went to Harvard, first as assistant professor, then became associate professor, professor holding the chair of Abbott and James Lawrence Professor of Chemistry, and department chairman. He has done considerable research work largely in the fields of kinetics of gas-phase reactions; thermochemistry of organic compounds, and enzyme catalyzed reactions. From 1940-44 he participated actively in work concerned with national defense and wartime projects. He was awarded the Medal of Merit in 1946.

professor initiate the student into the spirit of scientific research and scientific thinking. The authority of the graduate student over his individual problem teaches him a sense of personal responsibility, forces him to think independently; the free exchange of information and the running debates with fellow students on the research problems of the laboratory encourage a friendly spirit of competition and teach the student the true meaning of research team work—the free association of men aiming at a common objective. In what better way could a professor prepare a student for a career of growing independence and responsibilities than by expecting him



to explore on his own rather than take the instructions of his research professor blindly, and only to assist him in finding the correct path to follow?

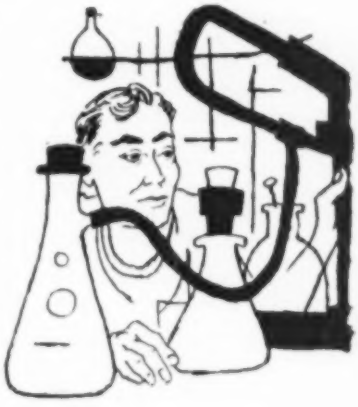
This system worked well, as the flowering of sciences in this country testifies. And so it is disturbing that major changes are being wrought in the system by the ever-growing flow to colleges of military research contracts. In the years immediately following the last war these contracts undeniably were almost indispensable to the recovery of college science. And even now most of them are so formulated and so administered that science is advanced without conflict with the best objectives of graduate education. But there are quite a few research projects which operate to obtain design data for the current rearmament effort, regardless of the true functions of the colleges, in short, projects which convert the graduate schools into commercial development establishments. This should be a matter of general concern. A custom is growing to make the graduate students the mainstay of such projects and to turn their work on the project into the focal point of their graduate training. There is too little independent research by students, too much demand for specified information by a specified date, too much interposition of an elaborate supervisory organization between the student and the professor, to regard this as good scientific training. This country is threatened with a generation of scientific workers who know how to carry out instructions and to follow in the footsteps of others, but who have not learned how to discover a rewarding research problem, how to plan the attack on it, and how to solve it. And whether the student is being trained for industrial leadership or, perchance, for the life of a college scientist, a good job is not being done this way.

Were the participation of graduate students in these activities motivated by natural inclinations and intellectual capacity only, one could not make such an issue of the matter. But, in fact, the students are frequently enlisted by rates of pay far in excess of other forms of graduate student aids, by recruitment into the project at an early phase of graduate training, when the students have no powers of discrimination between effective and faulty types of research training, and sometimes even by direct orders from departmental authorities.

All of this would not be happening if government funds were not having strong influence on the college teaching staffs, in fact on the colleges themselves. The possession of a large research con-

tract, whether scientifically desirable or not, has become a rich plum for reasons of prestige and personal finances. The institution stands to gain the usually substantial overhead. These are strong pressures, not always or easily resistible and the consequences not to be welcomed. The premium in the academic career is being placed not upon the excellence of lectures and of graduate training through personal research guidance, but upon qualities better suited to other walks of life. No wonder that one hears nowadays frequent complaints from students that their professors seem to have no time for them. Could it be that the current decrease in the number of science students is influenced by the hurried and indifferent teaching of sciences?

On the young Ph.D. level problems have also arisen. The total number of college jobs for the Ph.D.'s has grown rapidly because so many of them are now only half time or quarter time or even not at all on the teaching staff. But the chances of promotion to a tenure position have decreased proportionately, since the life-long commitments for senior staff positions cannot be much expanded on the strength of annually awarded research money. And so, the college career, which was never espe-



cially lucrative but was at least secure, must appear nowadays to a young Ph.D. as an almost hopeless gamble. Can blame be put on the best graduate students for tending to choose the comparative security and affluence of industrial positions? But what will be the effects of this trend on the quality of future training in graduate schools?

If this writer's conclusions are right, that the education of well-trained young scientists is vital to the welfare and perhaps the survival of the United States and that the great influx of military contract money is utilized for conflicting purposes, then the American public has a clear call to action.

This paper does not attempt to outline a coherent and clear program of remedies for this prevalent condition. However, a few obvious steps can be singled out here and there. The one that is most urgent is disappointingly unheroic. If the military research contracts do harm occasionally to scientific education, it is not because the Military is callous to the long-range needs of this country, but rather the reason is to be found in a shortage of technical personnel qualified to select and administer properly their research contracts. And so the first call to action could be a simple appeal to all

those who are practicing research and who believe in time-honored principles of scientific training, to assist the various military research establishments in the selection and administration of research. They need advisory work in screening the good from the bad proposals; even more there is need not for advisory but for full-time work in the administration of contracts, to insure the flow of needed information to the Department of Defense without damaging the chances of long-range survival. The application of a consistent policy is a must so that colleges should be doing only such research as is not in conflict with the principles of good education. The other military needs must be met by work of the well-established industrial laboratories of large corporations, by the industrial consulting firms, and by the many research companies that have sprung up since the last war. They are mostly operated by bright young men; they can deliver the desired information, so why not keep them real busy?

The much-buffeted National Science Foundation is at last in operation on a small scale. Its grants-in-aid for research may not appeal to an earnest empire-builder, but right now there appears to be no better way to make interesting research possible and to assist new scientists into the world of research. Its graduate fellowships permit a good student to learn what science is without committing himself for three years to the improvement of something like adhesive tape or a truly unimportant object. The taxpayers could help the National Science Foundation in maintaining its established high standards by giving freely of their time and their thinking to its problems.

An appeal necessarily need not be made to that part of the public which is known as American industry, to assist in financing the task of scientific training. It has done this in the past. But concern is felt over the comments of some in the industrial world specifically, that the influx of government money makes industrial gifts and fellowships seem puny and unnecessary. Far from it! Influx of government money has set up a state of unstable equilibrium in colleges and a little here or there will cause great changes in the final state. There are many unavoidable limitations to the scope of NSF fellowships. Where these cease to be effective, industrial fellowships should step in to ensure that, regardless of the income of the parents, the truly brilliant youngster will have a chance at a fine training. The lot of a college professor who would rather spend his or her time on education than on extracurricular activities, seems to be getting harder and harder as the time goes on. American Industry is the great customer for graduate students. It seems to value the training, judging by the salary offers. Why not counteract the current trend and make education the most rewarding activity of a college staff member?

A concluding thought—how about an effort to rid the populace of the belief that the scientific community is composed exclusively of useless long-hairs and makers of hell weapons? How about selling the concept of the scientists as members of a large team, made of practical people, the humanists, the medics and so many others, all of whom are indispensable to the happy future of this land.

Talk given at a Convocation on Science and Human Values at Mt. Holyoke College.

Thermodynamic Evaluation of Binary and Ternary Liquid Systems

Kurt Wohl **University of Delaware, Newark, Delaware**

Corrections

Equation (59*a*), page 242, should be as follows:

$$C_1 = q_1[(3a_{112} + 3a_{133} + 3a_{223} - 6a_{123}) + 8a_{1112} + 4a_{1113} + 4a_{1333} + 4a_{2223} - 12a_{1123}]$$

$$C_2 = q_2[(3a_{112} + 3a_{133} + 3a_{223} - 6a_{123}) + 8a_{2223} + 4a_{1222} + 4a_{1112} + 4a_{1333} - 12a_{1223}]$$

$$C_3 = q_3[(3a_{112} + 3a_{133} + 3a_{223} - 6a_{123}) + 8a_{1333} + 4a_{2333} + 4a_{2223} + 4a_{1112} - 12a_{1233}]$$

In Equations [61(*a*), (*b*), and (*c*)], the signs before the terms $3z_2z_3D_{23}q_1/q_2$, $3z_1z_3D_{13}q_2/q_3$, and $3z_1z_2D_{12}q_3/q_1$, respectively, should be plus instead of minus.

Addenda

A Symmetrical Form of Equations for Excess Free Energy and Activity Coefficients of Ternary Systems

In order to arrive at equations of the Margules type for ternary systems which are symmetrical and unambiguous with respect to the definition of the ternary constant, one may proceed as follows:

EDITOR'S NOTE

This paper serves as a supplementary note to the above-titled paper, *Trans. Am. Inst. Chem. Engrs.*, 42, 215-249 (1946). The main progress which this note represents over the published paper is that the new form of the equations permits a better-founded prediction of the behavior of ternary systems from that of the three binary pairs. The corrections and addenda follow:

(a). Three-suffix equation.

Use Equation (51) and (52*a*), *Trans. Am. Inst. Chem. Engrs.*, 42, 215 (1946), but replace Equation (52*b*) by

$$C^* = \frac{3}{2}(a_{112} + a_{122} + a_{113} + a_{133} + a_{223} + a_{233}) - 6a_{123}$$

There follows, instead of Equation (53):

$$\Delta G/2.3\,RT = x_1x_2(x_1A_{2-1} + x_2A_{1-2}) + x_1x_3(x_1A_{3-1} + x_3A_{1-3}) + x_2x_3(x_2A_{3-2} + x_3A_{2-3}) + x_1x_2x_3[\tfrac{1}{2}(A_{1-2} + A_{2-1} + A_{1-3} + A_{3-1} + A_{2-3} + A_{3-2}) - C^*]$$

and instead of Equation (54*a*):

$$\log \gamma_1 = x_2^2[A_{1-2} + 2x_1(A_{2-1} - A_{1-2})] + x_3^2[A_{1-3} + 2x_1(A_{3-1} - A_{1-3})] + x_2x_3[\tfrac{1}{2}(A_{2-1} + A_{1-2} + A_{3-1} + A_{1-3} - A_{2-3} - A_{3-2}) + x_1(A_{2-1} - A_{1-2} + A_{3-1} - A_{1-3}) + (x_2 - x_3)(A_{2-3} - A_{3-2}) - (1 - 2x_1)C^*]$$

The values of $\log \gamma_2$ and $\log \gamma_3$ follow from $\log \gamma_1$ according to the rotation principle. *In simple cases a value* $C^* = 0$

can be expected,† *so that the ternary system can be calculated from binary data.* The equations for the symmetrical three-suffix case ($A_{2-1} = A_{1-2}$, $A_{3-1} = A_{1-3}$, $A_{2-3} = A_{3-2}$) and for the two-suffix case ($C^* = 0$, in addition to the three above conditions) follow immediately.

The symmetrical equation for log (γ_1/γ_2) can be derived directly from the excess free energy with the help of the formula

$$\log \frac{\gamma_1}{\gamma_2} = \frac{\partial}{\partial x_1}\left(\frac{\Delta G}{2.3RT}\right) - \frac{\partial}{\partial x_2}\left(\frac{\Delta G}{2.3RT}\right)$$

The result is:

$$\begin{aligned}\log(\gamma_1/\gamma_2) &= x_2^2 A_{1-2} - x_1^2 A_{2-1} \\ &+ 2x_1x_2(A_{2-1} - A_{1-2}) \\ &+ x_3\Big[2x_1A_{3-1} - 2x_2A_{3-2} \\ &+ x_3(A_{1-3} - A_{2-3}) \\ &+ (x_2 - x_1)[\tfrac{1}{2}(A_{1-2} \\ &+ A_{2-1} + A_{1-3} + A_{3-1} \\ &+ A_{2-3} + A_{3-2}) - C^*]\Big]\end{aligned}$$

The values of log (γ_2/γ_3) and log (γ_3/γ_1) follow according to the rotation principle.

(b). Four-suffix equation.

Use Equations (58), (59*a*) and (59*c*) of the paper mentioned with the simplification of replacing z_1, z_2 and z_3 by x_1, x_2 and x_3, respectively, and of making q_1, q_2 and q_3 equal to one. Replace the three equations (59*b*) by the following:

$$\begin{aligned}C_1^* &= \tfrac{1}{2}(3a_{112} + 4a_{1112} + 3a_{122} + 4a_{1222} \\ &+ 3a_{113} + 4a_{1113} + 3a_{133} + 4a_{1333} \\ &+ 3a_{223} + 4a_{2223} + 3a_{233} + 4a_{2333}) \\ &- 6a_{123} + 4a_{1112} + 4a_{1113} - 12a_{1123}\end{aligned}$$

$$\begin{aligned}C_2^* &= \tfrac{1}{2}(3a_{112} + 4a_{1112} + 3a_{122} + 4a_{1222} \\ &+ 3a_{113} + 4a_{1113} + 3a_{133} + 4a_{1333} \\ &+ 3a_{223} + 4a_{2223} + 3a_{233} + 4a_{2333}) \\ &- 6a_{123} + 4a_{2221} + 4a_{2223} - 12a_{2213}\end{aligned}$$

$$\begin{aligned}C_3^* &= \tfrac{1}{2}(3a_{112} + 4a_{1112} + 3a_{122} + 4a_{1222} \\ &+ 3a_{113} + 4a_{1113} + 3a_{133} + 4a_{1333} \\ &+ 3a_{223} + 4a_{2223} + 3a_{233} + 4a_{2335}) \\ &- 6a_{123} + 4a_{3331} + 4a_{3332} - 12a_{3312}\end{aligned}$$

There follows instead of Equation (60)

$$\begin{aligned}\Delta G/2.3RT &= x_1x_2(x_1A_{2-1} + x_2A_{1-2} \\ &- x_1x_2D_{12}) + x_1x_3(x_1A_{3-1} \\ &+ x_3A_{1-3} - x_1x_3D_{13}) \\ &+ x_2x_3(x_2A_{3-2} + x_3A_{2-3} \\ &- x_2x_3D_{23}) + x_1x_2x_3 \\ &[\tfrac{1}{2}(A_{1-2} + A_{2-1} + A_{1-3} \\ &+ A_{3-1} + A_{2-3} + A_{3-2}) \\ &- (x_1C_1^* + x_2C_2^* + x_3C_3^*)]\end{aligned}$$

and instead of Equation (61*a*)

$$\begin{aligned}\log\ \gamma_1 &= x_2^2[A_{1-2} + 2x_1(A_{2-1} \\ &- A_{1-2} - D_{12}) + 3x_1^2D_{12}] \\ &+ x_3^2[A_{1-3} + 2x_1(A_{3-1} \\ &- A_{1-3} - D_{13}) + 3x_1^2D_{13}] \\ &+ x_2x_3[\tfrac{1}{2}(A_{2-1} + A_{1-2} \\ &+ A_{3-1} + A_{1-3} - A_{2-3} \\ &- A_{3-2}) + x_1(A_{2-1} - A_{1-2} \\ &+ A_{3-1} - A_{1-3}) + (x_2 - x_3) \\ &(A_{2-3} - A_{3-2}) + 3x_2x_3D_{23} \\ &- x_1C_1^* - (1 - 3x_1)(x_1C_1^* \\ &+ x_2C_2^* + x_3C_3^*)]\end{aligned}$$

Values of log γ_2 and log γ_3 follow according to the rotation principle.

The corresponding equation for log γ_1/γ_2 can be derived from the four-suffix equation for the excess free energy by the general procedure used before. One obtains:

$$\begin{aligned}\log\ \gamma_1/\gamma_2 &= x_2^2A_{1-2} - x_1^2A_{2-1} \\ &+ 2x_1x_2[A_{2-1} - A_{1-2} \\ &+ D_{12}(x_1 - x_2)] + x_3 \\ &\Big[2x_1A_{3-1} - 2x_2A_{3-2} + x_3 \\ &(A_{1-3} - A_{2-3} - 2x_1D_{13} \\ &+ 2x_2D_{23}) + \tfrac{1}{2}(x_2 - x_1) \\ &(A_{1-2} + A_{2-1} + A_{1-3} \\ &+ A_{3-1} + A_{2-3} + A_{3-2}) \\ &- x_1(2x_2 - x_1)C_1^* + x_2(2x_1 \\ &- x_2)C_2^* + x_3(x_1 - x_2)C_3^*\Big]\end{aligned}$$

Values of log γ_2/γ_3 and log γ_3/γ_1 follow according to the rotation principle.

Two main simplifications of all the four-suffix equations presented are possible. They are independent of each other—

1. **Values D_{12}, D_{13} and D_{23} may all be zero,**
2. **Values C_1^*, C_2^* and C_3^* may be equal.**

The latter condition produces one C^*-term which takes the place of C^* in the three-suffix equations just given. *In simple cases a value $C^* = 0$ can be expected.* If the simplifications 1, and 2 are both valid, the three-suffix equations result. Extension to quaternary systems ‡ is entirely feasible.

† J. Happel drew attention to the fact that the statement: "In especially simple cases C will be zero," on p. 241 of the paper mentioned is not justified if applied to the old value of C given by Equation (52*b*) of that paper. A more appropriate statement without change of equations was made in the paper mentioned further below.

‡ Jordan, D., Gerster, J. A., Colburn, A. P., and Wohl, K., *Chem. Eng. Progress*, **46**, 601 (1950).

NOTED AND QUOTED

Men, Management and Mobilization

What seems like so much useless red tape to those new in Government is really nothing more than a projection in a much larger organization of procedures with which all those working for large companies are familiar. In Government, the largest organization of all, these procedures provide for the reconciling of the many very different, and sometimes conflicting, public interests. Each unit with its different responsibility must have its opportunity to make known its viewpoint before a decision can be truly cast in the public interest. As an organization becomes larger in size, the necessity for assuring that all aspects of any given problem are recognized and given adequate consideration requires procedures which take on an appearance of being more complex. In reality, the procedures are basic procedures applied to more complex situations. . . . .

However, the Government must face up to a [necessary] step, namely, the execution of a policy whereby industry people working for the Government are regularly and periodically rotated. This plan not only serves to overcome many of the objections which businessmen have when coming to work for the Government—as well as the objections of their firms—but it also serves the Government in building up a large reserve of qualified and experienced people who would have the ability to serve the Government competently in case of full mobilization. Moreover, such a system would be of great advantage to those employers who furnish personnel to staff the defense agencies.

[Another] step which can be taken by the Government . . . is that of the creation of a reserve corps composed of those who have served and will serve in the future in the defense program. Such a reserve corps can be compared with the Army's military reserve corps and will be an invaluable backlog in meeting any future emergency likely to arise. From the Government mobilization standpoint, this reserve will consist of a roster of former Government executives who have returned to private industry with a full term, not less than six months, of service in which they have served in a responsible capacity.

—**Henry H. Fowler**
Former Director, Office of Defense Mobilization

CHEMICAL RESISTANT CEMENT REFERENCE SHEET

RAYMOND B. SEYMOUR and ROBERT H. STEINER

The Atlas Mineral Products Co., Mertztown, Pa.

EPOXY CEMENT: An infusible thermosetting plastic material based on the condensation product of epichlorohydrin and a dibasic phenol such as diphenylolpropane. The uncatalyzed cement mortar consists of a liquid epoxy resin premixed with an inert filler, such as carbon, silica or asbestos. A liquid catalyst or hardening agent is supplied in a separate container.

APPLICATION AND REMARKS: An epoxy cement mortar is prepared by intimately mixing the uncatalyzed epoxy cement mortar with the liquid catalyst just prior to use. The liquid catalyst consists of a solution of an amine which causes the mortar to harden at ordinary temperatures. The mortar is used for joining acid-proof brick and tile for lining chemical vessels, stacks, floors, or pipes. It can also be used to cast self-supporting chemical resistant process equipment. When allowed to harden, epoxy cements have excellent resistance to many nonoxidizing agents including acids, alkalies, salts and many organic solvents. One of the outstanding properties of epoxy cements is their ability to cure in contact with Portland cement or metallic surfaces and thus bond tenaciously to a wide variety of construction materials.

CHEMICAL COMPOSITION: The uncatalyzed mortar usually consists of low molecular weight liquid epoxy resins blended with inert fillers, such as carbon, silica or asbestos. Resins of this type can be prepared from bisphenol A and epichlorohydrin.

WORKABILITY: Catalyzed epoxy cement mortars can be readily trowelled onto brick or tile or almost any other type of surface. Specific formulations can be cast or compression-molded to form special shapes. A working life of 30 to 60 min. at 77° F. is typical. A preliminary set is obtained within a few hours but several days are required for the cement to attain maximum strength and optimum chemical resistance.

MACHINABILITY: Cast or molded shapes can be sawed, ground, turned, drilled and tapped with ordinary metal-working equipment. Molded or cast parts can be readily cemented together with epoxy cements.

TEMPERATURE LIMITATIONS: Room temperature setting epoxy cements are not recommended for use at temperatures above 212° F.

A TYPICAL CARBON-FILLED EPOXY CEMENT

MECHANICAL AND PHYSICAL PROPERTIES

Tensile Strength, lb./sq.in. @ 75° F.	1,500
Elongation, %	< 1
Impact Notch, Izod, ft.lb./in.	0.5
Flexural Strength, lb./sq.in. @ 75° F.	6,000
Compressive Strength, lb./sq.in. @ 75° F.	16,000
Specific Gravity	1.4

CORROSION RESISTANCE

	C	H
ACIDS		
Acetic, 10%	E	E
Acetic, glacial	F	P
Benzene, sulfonic, 10%	E	E
Benzoic	E	E
Boric	E	E
Butyric, 100%	G	F
Chloroacetic, 10%	E	E
Chromic, 5%	F	N
Citric	E	E
Fatty acids	E	E
Fluosilicic*	E	E
Formic, 90%	E	F
Hydrobromic	E	E
Hydrochloric	E	E
Hydrocyanic	E	E
Hydrofluoric*	E	N
Hypochlorous	P	N
Lactic	E	E
Maleic, 25%	E	E
Nitric, 5%	F	N
Oleic	E	E
Oxalic	E	E
Perchloric	E	E
Phosphoric	E	E
Picric	E	E
Stearic	E	E
Sulfuric, 50%	E	E
Sulfuric, 80%	F	N
Oleum	N	N
Mixed acids, 57% H_2SO_4, 28% HNO_3	N	N
ALKALIES		
Ammonium hydroxide	E	E
Calcium hydroxide*	E	E
Potassium hydroxide*	E	E
Sodium hydroxide*	E	E
ACID SALTS		
Alum or Aluminum sulfate	E	E
Ammonium chloride, nitrate, sulfate	E	E
Copper chloride, nitrate, sulfate	E	E
Ferric chloride, nitrate, sulfate	E	E
Nickel chloride, nitrate, sulfate	E	E
Stannic chloride	E	E
Zinc chloride, nitrate sulfate	E	E
ALKALINE SALTS		
Barium sulfide	E	E
Sodium bicarbonate	E	E
Sodium carbonate	E	E
Sodium sulfide	E	E
Trisodium phosphate	E	E
NEUTRAL SALTS		
Calcium chloride, nitrate, sulfate	E	E
Magnesium chloride, nitrate, sulfate	E	E
Potassium chloride, nitrate, sulfate	E	E
Sodium chloride, nitrate, sulfate	E	E
GASES		
Chlorine, dry	F	N
Chlorine, wet	P	N
Sulfur dioxide, dry	E	E
Sulfur dioxide, wet	E	E
ORGANIC MATERIALS		
Acetone	E	P
Alcohol, methyl, ethyl	E	E
Aniline	F	N
Benzene	E	E
Carbon tetrachloride	E	E
Chloroform	E	E
Ethyl acetate	E	E
Ethylene chloride	E	F
Formaldehyde, 37%	E	E
Phenol, 5%	E	E
Refinery crudes	E	E
Trichloroethylene	E	F
PAPER MILL APPLICATIONS		
Kraft liquor*	E	E
Black liquor*	E	E
Green liquor*	E	E
White liquor*	E	E
Sulfite liquor	E	E
Chlorite bleach	P	N
Alum	E	E
PHOTOGRAPHIC INDUSTRY		
Developers	E	E
General use	E	E
Silver nitrate	E	E
FERTILIZER INDUSTRY		
General use	E	E
STEEL INDUSTRY		
Sulfuric acid pickling	E	E
Hydrochloric acid pickling	E	E
H_2SO_4-HNO_3 acid pickling	F	P
TEXTILE INDUSTRY		
General use	E	E
FOOD INDUSTRY		
General use	E	E
Breweries	E	E
Dairies	E	E
MISCELLANEOUS INDUSTRIES		
Plating	E	E
Petroleum	E	E
Tanning	E	E
Oil and soap	E	E
Water and sewer	E	E

* *Carbon filled*

RATINGS:

E—No attack.
G—Appreciably no attack.
F—Some attack but usable in some instances.
P—Attacked—not recommended.

N—Rapidly attacked.
C—Cold—70° F.
H—Hot—200° F. or boiling point of test solution.

No. 20

NATIONAL SURVEY QUESTIONNAIRE
A Report to the Members

By Lloyd B. Smith, *Chairman, Questionnaire Sub-Committee*

Exactly 7,802 members of the American Institute of Chemical Engineers, almost two thirds of the membership, heeded the admonition printed on the front of the Questionnaire mailed to them last fall and did not throw it away. This number accounted for the extra mail that arrived in the Executive Secretary's office during December and January in an amazing and gratifying demonstration of the desire of the majority of the membership to cooperate in an effort to improve the Institute. Letters came from soldiers in India and Korea, from South America, Europe and other parts of the world, several from our friends and neighbors in Canada, and from every State in the U.S.A. except one. The questionnaire was well received, as the response will attest (more than 64%). Some compliments were stated and some thought a repetition of such a procedure would be in order; not too frequently, of course. One must be reasonable about this sort of thing.

Almost half (44%) of the returned questionnaires contained added comments which varied in length from one or two handwritten sentences to three and four typewritten pages. Several welcomed the opportunity to blow off steam. It was evident that few, if any, withheld any punches, and these frank comments were exactly the type desired. Most of the responses were helpful and constructive in their content. The majority of the comments dealt with "C.E.P.," some with grades of membership, the voice of Junior members in nominating and voting, with local sections, the economic status of engineers, and many suggestions having to do with various ideas on what the Institute should or should not do. The analysis and correlation of these 3,465 comments is a time-consuming job but is now underway.

Just a word about what has been done, what is underway, and what is planned may be in order. The questionnaires were mailed to the membership on or about Dec. 1, 1952. Instructions were included to return them not later than Jan. 15, 1953. Two weeks were allowed for mails to arrive and the business of receiving the questionnaires was terminated on Feb. 1, 1953. Each questionnaire as received was stamped with a number, consecutively, by the Secretary's office and the name of a state, taken from the postmark, was written on each questionnaire. The purpose of the number is to tie in written comments on a questionnaire with other data on the same questionnaire if desired. The purpose of the name of the state is to make possible a segregation of opinions to determine possible variations in different parts of the country. As the questionnaires were received, numbered, and marked by states, Mr. Tyler expressed them to the writer in Baton Rouge. They were then sorted into states by volunteers from the Baton Rouge Section. Each state was then given an I.B.M. code number and on Feb. 6, 1953, the questionnaires were turned over to the International Business Machine Corp. for processing. The numerical results were received from the I.B.M. Corp. on March 6, 1953. A call for help was again answered by volunteers from the Baton Rouge Section and the questionnaires were again sorted into those containing comments and those without comments. Those containing comments were divided into five piles of about 700 each and distributed to various members of the questionnaire subcommittee for analysis and correlation according to a prearranged plan. In order to eliminate the possibility of one of the correlators recognizing an individual from his comments, distribution was such that no questionnaire was reviewed by a correlator from the same state. These five groups and their directors working on

(*Continued on page 28*)

TABLE 1.—DISTRIBUTION OF QUESTIONNAIRES BY STATES

State	Number Mailed Out	Returned		Returned With Comments	Group Considering Comments
		Total Number	%	Number	
Alabama	105	70	66.7	34	*A*
Arizona	6	3	50.0	2	*A*
Arkansas	37	24	64.9	14	*A*
California	795	539	67.8	283	*A*
Colorado	63	44	69.8	26	*A*
Connecticut	192	102	53.1	45	*A*
Delaware	582	429	73.7	165	*A*
District of Columbia	63	48	76.2	17	*A*
Florida	55	36	65.5	22	*A*
Georgia	79	52	65.8	20	*B*
Idaho	29	23	79.3	14	*B*
Illinois	691	433	62.7	196	*B*
Indiana	241	163	67.6	85	*B*
Iowa	35	24	68.6	15	*B*
Kansas	60	47	78.3	27	*B*
Kentucky	151	82	54.3	43	*B*
Louisiana	264	172	65.2	68	*B*
Maine	12	8	75.0	4	*B*
Maryland	238	158	66.4	69	*B*
Massachusetts	387	238	61.5	102	*C*
Michigan	381	256	67.2	103	*C*
Minnesota	80	56	70.0	24	*B*
Mississippi	15	14	93.3	8	*B*
Missouri	337	210	62.3	75	*B*
Montana	10	8	80.0	3	*B*
Nebraska	8	5	62.5	4	*B*
Nevada	15	11	73.3	...	
New Hampshire	10	5	50.0	...	
New Jersey	1,028	547	53.2	241	*C*
New Mexico	23	16	69.6	6	*C*
New York	1,501	937	62.4	430	*D*
North Carolina	40	23	57.5	13	*B*
North Dakota	9	5	55.6	3	*B*
Ohio	733	489	66.7	235	*C*
Oklahoma	229	156	68.1	86	*E*
Oregon	15	11	73.3	5	*B*
Pennsylvania	1,076	695	64.6	310	*E*
Rhode Island	21	10	47.6	4	*B*
South Carolina	42	20	47.6	10	*B*
South Dakota	2	...	....	...	
Tennessee	261	176	67.4	94	*E*
Texas	872	567	65.0	237	*D*
Utah	24	19	79.2	8	*C*
Vermont	2	1	50.0	...	
Virginia	156	100	64.1	28	*E*
Washington	174	111	63.8	26	*D*
West Virginia	432	256	59.3	99	*E*
Wisconsin	69	54	78.3	21	*E*
Wyoming	15	10	66.7	3	*E*
Canada	152	88	57.9	51	*E*
Other Foreign	270	51	18.9	18	*A*
Miscellaneous *	...	200	....	69	*A*
Total	12,087	7,802	64.5	3,465	

* Those with illegible postmarks.

Extensive Course in Mineral Engineering Termed Successful at Biloxi Meeting

A successful experimental departure from conventional programming in Institute meetings was witnessed by those who journeyed to Biloxi, Miss., during the early part of March. A three-phase meeting was presented by the national program committee and, for the first time in the history of the Institute, the chemical engineering profession discussed intensively the techniques of another engineering discipline. Two of the three days featured a symposium on mineral engineering techniques, in which the fields of flotation, sizing, and sink-and-float methods were carefully and thoroughly explored in an attempt to adapt and improve these mineralogical tools which are now finding increased usefulness in the chemical engineer's bag of tricks.

The second phase of the meeting represented a session for the executive and administrator, and an afternoon was given over to the discussion of the problem of successful communication to a staff. Engineering and development represented the third phase and these were well taken care of by several symposia covering fluid mechanics, processing, hydrometallurgical techniques, and general papers on kinetics and heat transfer.

Biloxi lived up to its advance billing, and balmy weather greeted the engineers for the first few days. The resort feature gave a centrality to the meeting, even though the 500 who attended had to be housed to some extent in hotels other than the headquarters. The Buena Vista was the gathering point and its lobby and verandas were the location of the many extracurricular meetings and conferences for which Institute conventions are noted. The chief social function of the meeting was a seafood jamboree which served a sumptuous meal of Gulf seafood specialties to practically all the chemical engineers —practically all—for one engineer demanded, and got, a steak. A variety show and dancing rounded out the jamboree night.

Left to right: J. V. Roach, Witco Chemical Co.; Mrs. J. V. Roach; Mrs. T. C. Landrum and T. C. Landrum, Esso Standard Oil Co., and chairman of the Hotel and Meeting Rooms Committee.

A group of speakers who presented general technical papers. Left to right: LeRoy A. Bromley, University of California; J. C. Carver, C. G. Rudershausen and H. F. Rase, University of Wisconsin.

Lloyd B. Smith of the Esso Standard Oil Co., Baton Rouge, La., gave a preliminary report on the results of the questionnaire which the Institute sent several months ago to all members. There is a first report on the results in this issue of "C.E.P.," page 17.

Technical Program

A. B. Metzner of the University of Delaware won the Institute's scroll for having the best-presented paper. This judging of paper delivery and platform technique is done at every Institute meeting to encourage engineers in effective oral methods. The scroll will be

Bus departure for Bellingrath Gardens trip.

given to Metzner at a meeting of his local section. The judging team, headed by Worthy T. Boyd of Esso Standard Oil Co., Baton Rouge, La., felt that of all the engineers, Metzner's presentation of his paper, titled "Pipeline Design for non-Newtonian Fluids," was the best.

The editor regrets that it is impossible to brief every paper given at the meeting in this news story. However, since most of the articles will probably appear shortly in "C.E.P." or in the separate publication series, the full texts will be available to those interested.

A report on the potential uses and industrial applications of radioactive materials was made by L. E. Brownell, W. W. Meinke, E. W. Coleman, and J. V. Nehemias, of the University of Michigan Memorial Phoenix Project. Professor Brownell reported on the work he had been doing with a cobalt 60 source obtained from the Chalk River, Canada, reactor. Primarily, the work at Michigan has been concerned with the use of the radioactive source for industrial processes such as food sterilization. According to Professor Brownell, a dose of nearly 3,000,000 R.E.P. is required to destroy microorganisms, and as small a dose as 12,000,000 R.E.P. will destroy the trichinosis cycle in contaminated pork. Chemical reactions are also promoted by gamma radiation, and specifically he mentioned the chlorination of benzene, which proceeds rapidly under such radioactive sources to form benzene hexachloride.

Another important technological development which came out of nuclear work, was reported by David H. North-

Speakers at the Mineral Techniques Symposium, seated, left to right: N. Morash, chairman; A. E. Anderson, Bethlehem Cornwall Corp.; I. M. LeBaron, International Minerals and Chemical Corp.; E. H. Crabtree, Eagle-Picher Co.; and N. Arbiter, Columbia University. Standing: Foster Crampton, International Minerals and Chemical Corp.; P. L. de Bruyn, Massachusetts Institute of Technology; E. W. Gieseke; G. Gutzeit, General American Transportation Corp.; C. L. Mantell, Newark College of Engineering; and A. M. Gaudin, Massachusetts Institute of Technology.

M. O. Gernand and J. F. Ross, both of Esso Labs., did a great job with the tape recording.

A group who presented general technical papers, left to right: L. E. Brownell, University of Michigan; R. M. Cohen, Iowa State College; David H. Northrup, Cambridge Corp.; and A. N. Hixson, chairman of this session.

Sizing Devices panel discussion included C. C. Coscia, General American Transportation Corp.; E. J. Roberts, Dorr Co.; W. Dyrenforth, International Minerals and Chemical; S. E. Erickson, M. A. Hanna Co.; P. V. Mancini, Deister Concentrator Co.; S. R. B. Cooke, panel leader, W. P. Stilz, Link-Belt Co.; and T. S. Leary, American Cyanamid Co.

A group of speakers on Streamlining Paper Shuffling Symposium. Left to right: N. O. Couvillon; Dr. Jack Sherman, Texas Co.; F. R. Fisher, chairman; C. C. Hurd, International Business Machines Corp.; and C. B. Barr, Sinclair Research Laboratories, Inc.

Sizing Devices panel in action: C. C. Coscia, General American Transportation Corp.; P. V. Mancini, Deister Concentrator Co.; S. E. Erickson, M. A. Hanna Co.; E. J. Roberts, Dorr Co.; S. R. B. Cooke, panel leader; W. Dyrenforth, International Minerals and Chemical Corp.; and W. P. Stilz, Link-Belt Co., presenting their case.

The Concentrating Devices panel included R. N. Hill, International Minerals and Chemical; P. V. Mancini, Deister Concentrator Co.; R. J. Piros, International Minerals and Chemical; and E. J. Roberts, Dorr Co. A. Stanley, National Lead Co., was panel leader; D. W. Oakley presided.

Alfred Smith, III, Cabot Carbon Co., member of Registration Committee; and R. V. Bailey, Tulane University, chairman of the Public Relations Committee.

Symposium on Hydrometallurgical Processes. Left to right: F. M. Stephens, Jr., Battelle Memorial Institute; Frank McGarvey, who presented Robert Kunin's paper; John W. Clegg who presided; and Norman A. Spector, Program and Technical Papers chairman for the Biloxi meeting, who presented Louis N. Allen, Jr.'s paper.

Left to right: Leo Friend and George Skaperdas of Kellogg; Professor R. L. Pigford, University of Delaware; and J. H. Rushton, Illinois Institute of Technology.

Left to right: standing: R. L. Pigford, University of Delaware, who presided over Fluid Mechanics Symposium; Rollin G. Taecker, Kansas State College; and A. B. Metzner, Colgate-Palmolive-Peet Co., who won the award for the best-presented paper. Seated: E. W. Comings, Purdue University; H. C. Ward, Georgia Institute of Technology; and R. H. Crowther, Kansas State College.

Herschel Cudd, acting director of Georgia Tech's State Engineering Experiment Station, and Mrs. Cudd.

Lloyd Smith reported to Council on results of the questionnaire.

Norman Morash, chairman, Mineral Engineering Techniques Symposium in Biloxi, and assistant chairman of the Technical Program for the 1954 Annual Meeting in New York.

rup, vice-president of the Cambridge Corp., when he discussed the A.E.C. or C.W.S. air filter. This new filter has been developed during the past eight to ten years and, according to Northrup, opens up an entirely new field of air cleaning for industrial application. The filter is now being used to supply virtually sterile air in rooms where antibiotics are packaged, and for many other production processes.

The filters are tested for the removal of 99.95% of particles of 0.3 μ size. A completely new test was devised to test the filter, according to Northrup, by using smoke particles and recording any particle that passes through the filter, by means of lenses and electronic indicators. The filters have a static resistance of 1 in. of water at rated airflow, which for a filter of 250 sq.ft. of filtering area is about 1000 cu.ft./min.

The filter paper used is a feltlike asbestos-bearing cellulose paper with the asbestos fibers microscopic in size and evenly distributed throughout the paper. Corrugated paper separators are inserted on both sides of the filter, the air passing down the flutes of the separator on one side, through the filtering medium, and out through the flutes of the separator on the other side.

The use of punched cards for analyzing experimental data can save time and money and can provide more accurate results with less work according to Dr. J. Sherman, who presented a talk on statistical analysis of punched cards. Sherman analyzed his statement by examples of work at the Beacon Research Laboratories of the Texas Co. He cited the case of single cylinder laboratory engines used for rating the antiknock performance of automotive gasoline. A large number of tests on a wide variety of gasolines, he said, was necessary to determine the correlations between the engines and the results from full-scale tests in cars on the road. Further tests are made periodically to check the reproducibility of the laboratory engines themselves and the precision of tests run on different engines. All these data are analyzed quickly by means of punched cards, and deviations from the expected precision can be detected and the causes corrected, he stated. In another example he said that fitting a linear curve to data points plotted on coordinate paper, depends upon the judgment of the engineer drawing the line as to which points fit the curve best. However, this personal judgment is not completely consistent, from time to time, or between different engineers, and by means of punched-card calculating machines it is possible to solve mathematical equations and determine standard curves which fit the data.

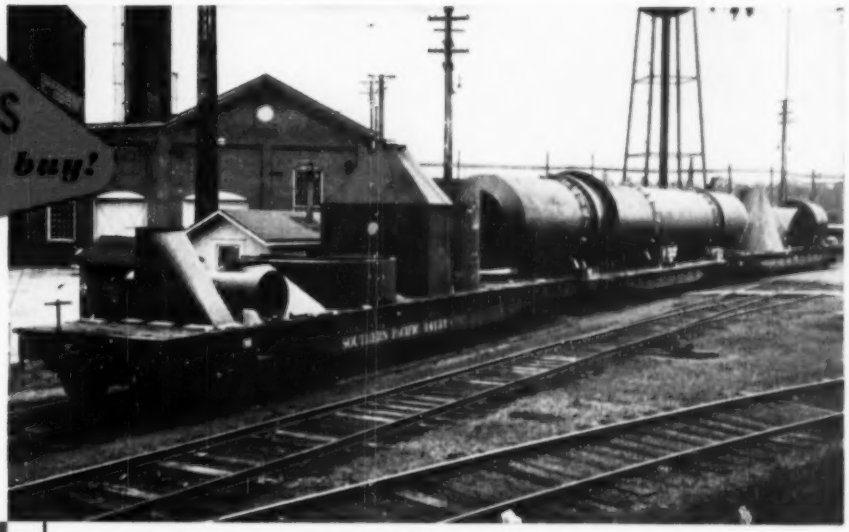
(Continued on page 22)

See Louisville for
CREATIVE DRYING ENGINEERING

PRODUCTION WILL BE UP 150%—COSTS DOWN 2/3's

WITH THIS NEW LOUISVILLE DRYER

KNOW
THE RESULTS
before you buy!



OLD DRYING PROCESS	
Installed Cost	$100,000
Annual Production (tons)	10,000
Drying Cost Per Ton	$ 3.11
Space Occupied	1,900 sq. ft.

PRE-DETERMINED	
Installed Cost	$ 95,000
Annual Production (tons)	25,000
Drying Cost Per Ton	$ 1.04
Space Occupied	1,000 sq. ft.

Ask for new treatise on subject of rotary dryers.

Other General American Equipment:
Turbo-Mixers, Evaporators, Dewaterers, Towers, Tanks, Bins, Filters, Pressure Vessels

PROCESS EQUIPMENT DIVISION
GENERAL AMERICAN
TRADE MARK

PROBLEM: manufacturer wanted to improve drying operation. Costs high, production low.

SOLUTION: manufacturer called in Louisville engineers.

These engineers started the Louisville method for predetermining results . . . and for fitting the dryer to the job.

Step 1. *Louisville engineers completely surveyed plant operations and previous drying methods.*

Step 2. *Recommended dryer design was checked in Louisville laboratory in actual drying test.*

Step 3. *A double check with larger pilot plant equipment actually installed in customer's plant.*

Step 4. *All factors determined and solved, full scale drying equipment was fabricated.*

Step 5. *Final installation will be checked for mechanical perfection and drying efficiency to insure anticipated results and purchaser's satisfaction.*

SUGGESTION: Why not call in a Louisville engineer to look over your drying operation? There's no obligation . . . and the results may pay big dividends.

LOUISVILLE DRYING MACHINERY UNIT
Over 50 years of creative drying engineering
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Dryer Sales Office: 139 South Fourth Street, Louisville 2, Kentucky • ***General Offices:*** 135 South LaSalle Street, Chicago 90, Illinois • ***In Canada:*** Canadian Locomotive Company, Ltd., Kingston, Ontario
OFFICES IN ALL PRINCIPAL CITIES

Left to right: L. C. Bearer, Phillips Petroleum Co.; Mrs. and Mr. Carleton Long, St. Joseph Lead Co. of Pennsylvania.

G. H. Beyer, Iowa State College; and Ward E. Pratt, Worthington Pump & Machine Corp.

C. W. Nofsinger, Kansas City; and C. G. Kirkbride, Houdry Process Corp.

BILOXI MEETING

(*Continued from page 20*)

The performance of a pulse extraction column for countercurrent liquid-liquid extraction was reported on by R. M. Cohen and G. H. Beyer of the Institute for Atomic Research, at Iowa State College. The pulse column essentially is typical of perforated plate extractive columns except that cyclic pulsations are imparted to the liquid in the column by means of a cam-driven bellows pulsator, and a diaphragm pump from which the checks have been removed. The column used in the investigation was of 1-in. diam., with perforated plates supported at 2-in. intervals. Each plate contains fifty-three tiny perforations, and extraction runs were made on a water-boric acid-isoamyl-alcohol system.

The authors found that when calculating the number of theoretical stages by the McCabe-Thiele method the over-all heights of a transfer unit were as low as 5.7 in. with water in the continuous phase, and capacities as high as 660 gal./(sq.ft.)(hr.) were achieved. They also found out that at high pulse frequencies, over-all H.T.U.'s are a function only of the flow ratio, whereas at low frequencies, over-all H.T.U.'s vary with the individual flow rates. They learned too that throughput in a pulse column is generally improved at high frequencies, although the use of high frequencies and amplitudes may cause emulsification. For the system investigated, they said, the pulse column was found to be most efficient at high throughput rates of the dispersed phase operating at moderate to high pulse frequencies of 35 to 72 cycles/min.

E. H. Crabtree, chairman of the Minerals Beneficiation Division of the American Institute of Mining and Metallurgical Engineers, opened the symposium on mineral engineering technique with a discussion on the history of flotation, its application, performance and how it works. To give the engineers an idea of how extensive a flotation plant might be he showed a picture of a plant that now handles 50,000 tons of copper ore a day.

The chemical theory of flotation and the functions of the various types of flotation reagents were covered by Dr. P. L. de Bruyn. Rapid strides have been made during the past ten years in understanding the mechanism of flotation, he said, and one of the most effective aids has been the application of radioactive tracer techniques.

A critical discussion of rate-controlling variables and rate equations for flotation systems was presented by Dr. Nathaniel Arbiter. A treatment was given for the general case where the concentration of mineral in the froth, rather than in the pulp, is rate-determining for recovery. Difficulties encountered in trying to prove experimentally the theoretically derived equations on kinetics were indicated.

Nonmetallic mineral flotation was described in a paper by Dr. I. M. LeBaron on phosphate concentration. Dr. LeBaron described a typical phosphate mining operation, complete with flow sheet, and illustrated how flotation fitted into the over-all picture. The various types of flotation as practiced in the Florida phosphate fields were described. These methods included such varied techniques as anionic flotation and cationic flotation as practiced in standard flotation machines and on pieces of equipment such as shaker tables, belt conveyors, underwater screens and Humphrey spirals.

Metallic mineral flotation was described by A. E. Anderson in a paper that dealt with the recovery of copper ore, by flotation, from iron-mine tailings. Improved metallurgy over the past thirty years was indicated in improved operations from a 1920 report showing a 0.43% copper feed producing a 2.96% copper concentrate with a 56.0% copper recovery to a 1952 report showing a 0.40% copper feed producing a highly satisfactory 24.9% copper concentrate with a 92.0% copper recovery.

Dr. C. L. Mantell in his paper on adsorption in the mineral industries noted the advances that had been made in flotation theory with the acceptance of the fact that the flotation mechanism was one of adsorption. Adsorption phen-

(*Continued on page 44*)

Jesse W. Mason, of Georgia Institute of Technology.

Mr. and Mrs. C. L. Schmidt. He is development manager at National Lead Co., South Amboy, N. J.

Mrs. Lloyd Smith, wife of Dr. L. Smith, co-chairman, Biloxi meeting.

How much better will Durcopumps do your pumping job?

The Series R Durcopumps are engineered and built for heavy duty pumping with less maintenance. They're available as standard items in 12 alloys from our own foundry.

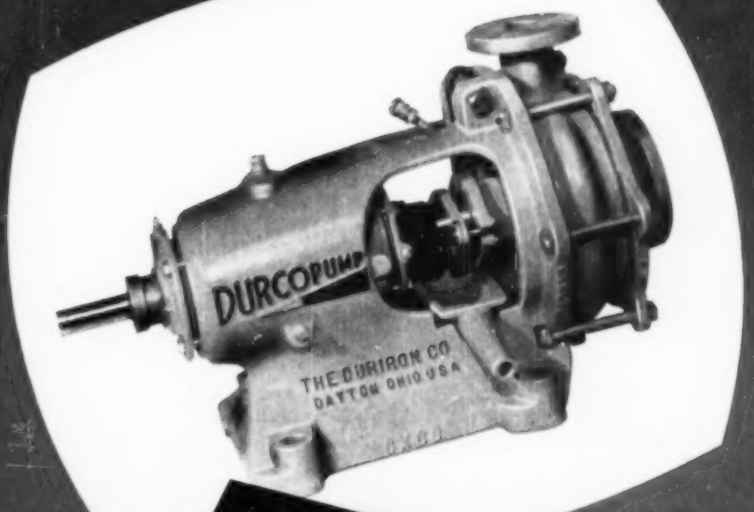
In many plants they're considered "standard equipment." *How much better* will they handle the corrosive you use?

Why not let us send you Durcopump Bulletin P/1? It will give you complete construction details and performance information to help you decide.

A DURCO representative near you will be happy to help you select the right pump in the right alloy.

WRITE OR PHONE FOR YOUR FREE COPY OF BULLETIN P/1

Series R Durcopumps



Duriron, Durichlor,
Durimet 20, Durco D-10M,
Chlorimet 2, Chlorimet 3, Monel, Nickel,
Inconel, Ni-Resist #2, 18-8-S-Mo, Cast Steel and Cast Iron

Sectional Index

1 General Information
2 Machinable Alloy
3 Duriron-Durichlor
4 Seal End Interchangeability
5 Pump Selector Table
6 Packing and Lubricant

The Duriron Company, Inc.
Dayton 1, Ohio

DURCO
CORROSION RESISTING ALLOYS & EQUIPMENT

How Much Does Pre-coating Cost You?

Do you have to use costly fibrous material to get a pre-coat surface that will hold diatomaceous earth or other filter aids you may be using? The high cost of asbestos fibers used day after day, to build up a base for pre-coating, far exceeds the cost of filter cloths.

SPARKLER
HORIZONTAL PLATE
FILTERS

have a lower pre-coat cost than any other type of filter. You may be surprised to find how much time and filter aid you can save in pre-coating horizontal filter plates.

Only a very thin pre-coat is required, and you can get brilliant clarity in filtration right from the start. No priming material is necessary to hold any kind of filter aid on Sparkler horizontal plates.

This pre-coat economy together with the time saving, quick change plate assembly feature make Sparkler Filters surprisingly low in operating cost.

Write Mr. Eric Anderson for engineering service on your filtering problems.

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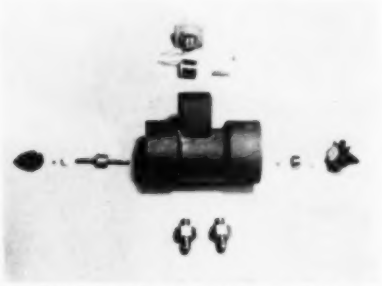
Sparkler Western Hemisphere Corp.
Mundelein, Ill., U.S.A.

Manufacturers of Fine Filtration Equipment for More Than a Quarter of a Century

NEW FLOWMETER MEASURES LB./HR.

A new electronic flowmeter that gives the rate of liquid flow in pounds, rather than gallons, per hour, thereby eliminating the density variable, was announced last month by the Gavco Corp., a subsidiary of General Aviation Corp. Although developed for use in jet aircraft, the gravimetric flow-measuring system has other industrial applications, particularly in chemical processes and in bulk storage, classification, and loading.

The principal features claimed for the flowmeter are accuracy (to within 1% for density and 0.5% for rate of flow),



Exploded view of sensing element used in new mass flowmeter developed by Gavco Corp. Parts in horizontal line form internal rotor that turns with fluid flow. They are designed to produce what is, in essence, a Venturi effect, reducing pressure drop through the unit to a negligible figure. The two couplings shown below are utilized to connect sampling lines to the density detector.

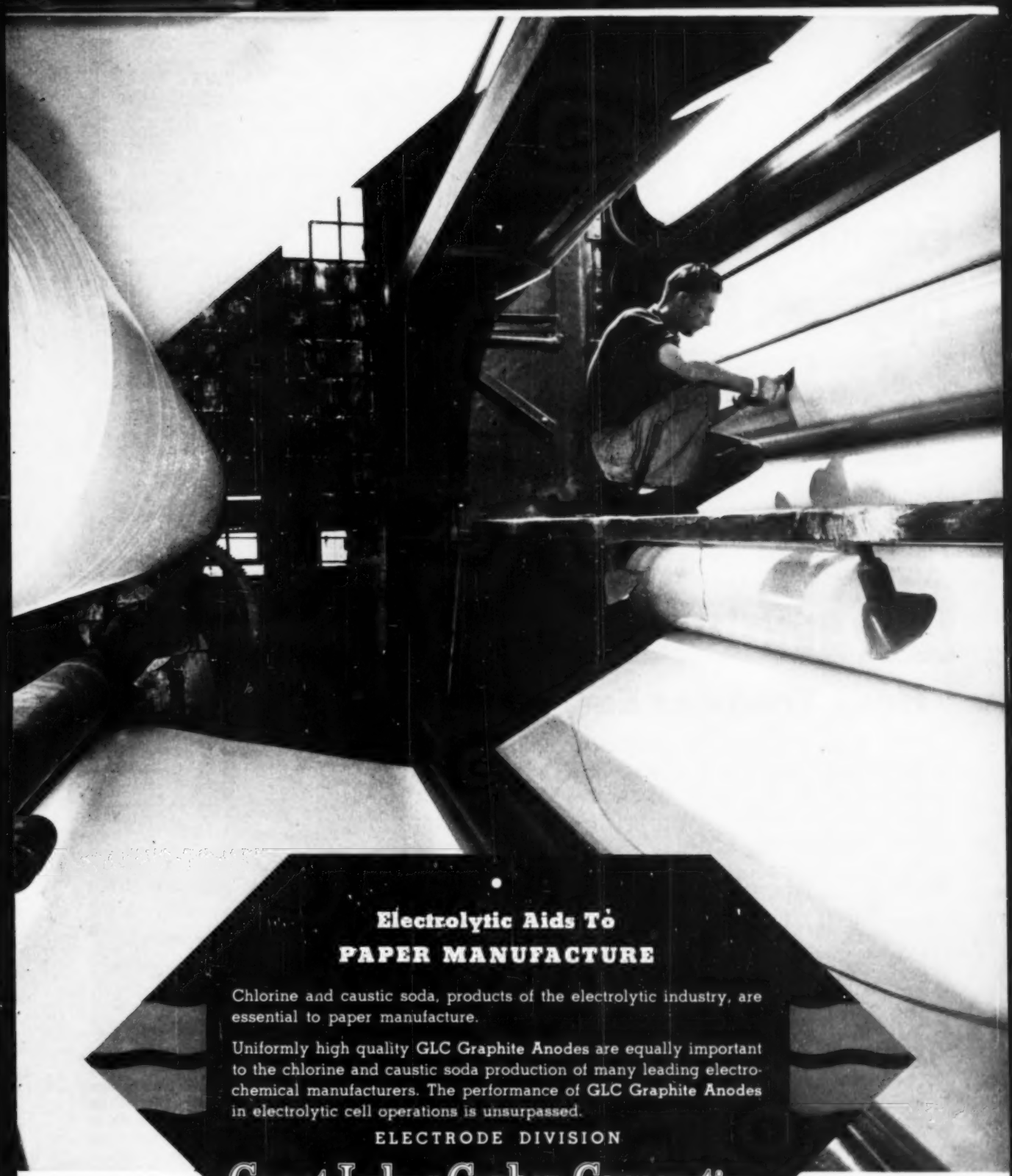
continuity (density of continuous flow is measured), and simplicity. The parts of the unit weigh less than 8 lb. in all and occupy 1/5 cu.ft.

The individual units include the volume-sensing element, which measures the flow in gallons; the density detector, which simultaneously weighs samples of the liquid; an integrator, which compensates the flow rate for the true weight of the fluid; and an indicator, which gives a reading in number of pounds per hour flowing through the lines. The unit is equipped to handle up to 60,000 lb./hr. in lines up to 1¼ in. in diameter.

U. S. RUBBER PLANS N. J. RESEARCH CENTER

A new research center devoted to rubber, chemicals, synthetics, textiles, and plastics is being planned by the U. S. Rubber Co. for Emerson, N. J. Construction is expected to begin this year. The center will have modern research facilities and will employ about 125 persons. The Emerson center will be about 12 miles from the general laboratories at Passaic, which will continue operating.

(More News on page 26)



Electrolytic Aids To
PAPER MANUFACTURE

Chlorine and caustic soda, products of the electrolytic industry, are essential to paper manufacture.

Uniformly high quality **GLC Graphite Anodes** are equally important to the chlorine and caustic soda production of many leading electrochemical manufacturers. The performance of **GLC Graphite Anodes** in electrolytic cell operations is unsurpassed.

ELECTRODE DIVISION

Great Lakes Carbon Corporation

Niagara Falls, N. Y. GLC Morganton, N. C.

Courtesy
West Virginia Pulp and Paper Company

Graphite Anodes, Electrodes and Specialties

Sales office: Niagara Falls, N. Y. **Other offices:** New York, N. Y., Chicago, Ill., Pittsburgh, Pa.

Sales Agents: J. B. Hayes, Birmingham, Ala., George O'Hara, Long Beach, Cal., Great Northern Carbon & Chemical Co. Ltd., Montreal, Canada.

"More Capacity from Existing Equipment?"

we use

Ewing Galloway

ACID-PROOF TANTALUM

Heat Transfer Equipment

"One of our problems was to add more capacity to sulphuric acid concentrator equipment. Even if we had space for them, it would take months to build more concentrators. By installing tantalum bayonet heaters and using higher steam pressures, we got the desired additional output. In some cases, concentrator capacity was increased 300 per cent."

TANTALUM BAYONET HEATER

used in Simonson-Mantius concentrator for H_2SO_4 recovery. More than 250 bayonet heaters have been made for this use. The first, installed in 1945, is still in service.

USE TANTALUM WITH ECONOMY for most acid solutions, corrosive gases or vapors; not with HF, alkalis, or substances containing free SO_3.

TANTALUM the most nearly perfect material of construction

Acid-Proof TANTALUM

22403C

Fansteel Metallurgical Corporation NORTH CHICAGO, ILLINOIS, U.S.A.

NEWS

(*Continued from page 24*)

STANOLIND INCREASES SULFUR RECOVERY

A unit designed to process daily 900,000 std. cu.ft. of hydrogen-sulfide-bearing gas for recovery of approximately 40,000 lb. of sulfur was opened last month north of Odessa, Tex., by the Stanolind Oil and Gas Co. Operated in conjunction with the company's North Cowden gasoline plant, the unit is the third such now operated by Stanolind. The Slaughter unit at Sundown, Tex., and the Elk Basin unit in Wyoming were completed earlier.

North Cowden feed gas to the sulfur-recovery unit contains 58% hydrogen sulfide and 39% carbon dioxide. In the process the gas first passes through a scrubber and then flows into a waste heat boiler, where it is burned with controlled air, producing sulfur dioxide and water. Combustion products from the boiler then flow to the first converter, where a major portion of the sulfur is produced. Maximum production of sulfur is obtained by means of a second converter. The unit is designed to recover 90% of the sulfur present in the feed gas. The heat released by the process is utilized to generate steam used within the process and elsewhere in the North Cowden plant.

The sulfur, produced in liquid form, flows into the sulfur pit, from whence it will be pumped for shipment or storage. At present it is being shipped as a solid, but future plans call for liquid form.

Both the sulfur unit and the gasoline plant are owned jointly by twenty-five separate companies and individuals and are operated by Stanolind.

MERCK MERGES WITH SHARP & DOHME

The principal terms of a merger of Merck & Co., Inc., Rahway, N. J., and Sharp & Dohme, Inc., Philadelphia, have been approved by the boards of directors of both companies, it was announced last month. The merger will join Merck's chemical research and manufacturing with Sharp & Dohme's pharmaceutical marketing.

The name of the combined company will be Merck & Co., Inc. The distinct functions of each of the firms will be maintained, and the business of Sharp & Dohme will be continued under the Sharp & Dohme name, operating as much as possible as a decentralized unit under its present management.

The officers of the new company will include George W. Merck as chairman of the board and as vice-chairman, John S. Zinsser, now chairman of Sharp & Dohme's board.

(*More News on page 30*)

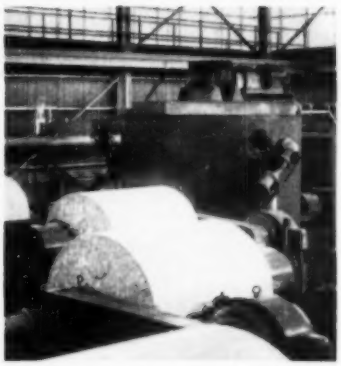
Turbo-Topics

TURBO-MIXER GENERAL AMERICAN

TURBO-MIXER, a division of

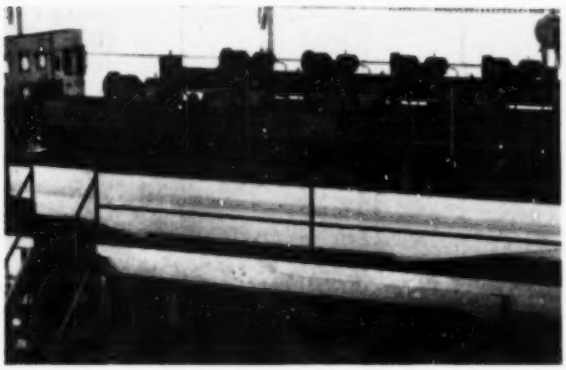
GENERAL AMERICAN TRANSPORTATION CORPORATION

TURBO INSTALLATION at Duval Potash Refinery



Left: *Turbo Slurry Mixers suspending ground potash ore*

Below: *Turbo-Floaters separating ground potash slurry in the roughing and cleaning circuits*



The modern Duval Sulphur & Potash Company plant recently opened at Carlsbad, New Mexico uses Turbo-Mixers exclusively in the refining operations. The Turbo-Mixers handle the major slurry suspension operations before and after flotation. The Turbo Floaters for the froth flotation of the potash ore are similar to the Turbo Floaters in the service of other refineries in the Carlsbad field.

Here is another example where an industrial leader called upon Turbo-Mixer to supply creative mixing devices for continuous duty—24 hours a day—every day. Call on Turbo for specialized help in supplying controlled agitation for optimum results.

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OTHER GENERAL AMERICAN EQUIPMENT:— **DRYERS • EVAPORATORS • DEWATERERS**

TOWERS • TANKS • BINS • FILTERS • PRESSURE VESSELS

VOLUNTEERS AND COMMITTEE MEMBERS FROM BATON ROUGE SECTION

Standing, left to right: E. J. Westbrook, Jerry Golden, C. V. Foster, M. O. Gernand, Ed Johnson, Worthy Boyd. Seated (Committee members): J. A. Polack, L. B. Smith (chairman), G. E. Montes. Not Present: Ken Rees, E. P. Breidenbach, A. O. Wikman, P. C. Davis.

TABLE 2.—SUMMARY OF RESULTS

Question No.	Description	Total Received
1.	Papers which are presented at National meetings of A.I.Ch.E. may be classified into four broad groupings: (1) Theoretical treatment of the fundamentals of chemical engineering, such as unit operations, processes, etc. (2) Practical treatment of chemical engineering unit operations, processes, equipment, corrosion, etc. (3) Commercial aspects, such as market analysis, sales engineering, product development, economics, and related subjects, and (4) Management problems, personnel problems, training and placement of technical people and the like. Please indicate your major preference of subject matter for the A.I.Ch.E. meetings by checking one only.	
	a. Fundamentals	1599
	b. Practical aspects	3686
	c. Commercial aspects	852
	d. Management problems	840
	e. No preference	650
2.	Do you feel that the requirements for Active membership are properly designed and maintained so that the attainment of this grade of membership is recognized as a real professional achievement in chemical engineering?	
	a. Yes	4995
	b. No	1191
	c. Undecided	943
	d. Don't know requirements	581
3.	Are you satisfied with the present procedure for nominating Officers and Directors?	
	a. Yes	4803
	b. No	502
	c. Undecided	563
	d. Don't know procedure	1818
4.	Are you satisfied with the present procedure for electing Officers and Directors?	
	a. Yes	5200
	b. No	559
	c. Undecided	481
	d. Don't know procedure	1439
5.	Papers presented at A.I.Ch.E. meetings are not necessarily published in "C.E.P." Would you favor publishing one- or two-page abstracts of those papers not published in full? Or instead of publishing abstracts would you prefer that reprints of all papers presented at meetings be made available for a nominal fee?	
	a. Abstracts in "C.E.P."	2223
	b. Reprints for a fee	2442
	c. Both	2615
	d. Neither	150
	e. No opinion	267
6.	Broadly considered, how well do you like "C.E.P."?	
	a. Very well	1360
	b. Well enough	4228
	c. Not very well	1868
	d. Not at all	137
	e. Undecided	118
7.	Which one of the following would you most like to see added to "C.E.P."? More articles or features on:	
	a. Political developments	173
	b. Medical developments	124
	c. Financial and corporate news	787
	d. Other sciences	721
	e. Market analysis	279
	f. Sales engineering	215
	g. Product development	1513
	h. Personnel	449
	i. Safety	169
	j. General economic aspects of chemical manufacturing and related industries	2391
	k. No opinion	664
8.	How much more would you be willing to pay as annual dues for additions of more technical material to "C.E.P."?	
	a. $0/year more	4127
	b. $1/year more	1232
	c. $2/year more	1457
	d. $3/year more	387
	e. $5/year more	460
9.	How much more would you be willing to pay as annual dues for additions to "C.E.P." of more items as listed in Question 7?	
	a. $0/year more	3857

(Continued on page 46)

NATIONAL SURVEY

(Continued from page 17)

this problem are as follows:

Group A—Baton Rouge Section—G. E. Montes.
Group B—Boston Section—R. K. Flitcraft.
Group C—Charleston Section—G. F. Jenkins.
Group D—Cleveland Section—D. J. Porter.
Group E—Oklahoma Section—M. F. Wirges.

The states being considered by each group may be ascertained by reference to the letter in Table 1. This table summarizes the number of questionnaires mailed out and the number returned by states.

Table 2 gives the results from the International Business Machine Corporation showing the numerical answers to the questions in the questionnaires. Correlations have not yet been made but these are in progress and will be reported at a later date. Some initial comments might be drawn from the figures presented in Table 2. For example, the following might be listed:

Question 1. The practical aspects of engineering appeal to the greatest number. Fundamental concepts are next in line. Eventually a tie-in with question 26 will be in order.

Question 2. If we look at the answer to this question compared with the answers to question 15 and 16 we find that the majority of our engineers are satisfied that they made the correct choice of a career, that they are recognized as professional men by their employers, and that most of them feel that the Active membership classification is a badge of professional achievement.

Question 3 and 4. A significant number of engineers are apparently satisfied with the present procedure for nominating and electing Officers and Directors of the Institute. This seems to be particularly significant when considered with question 21 which gives the total number of Active members answering the questionnaires as 2,956 whereas the favorable totals in question 3 and 4 are considerably above this number. In fact, only about 500 indicated dissatisfaction. There is a possibility here of varying opinion in different parts of the country and an effort will be made to break down these totals into either states or geographical areas.

Question 5. The numbers replying to the various parts of question 5 need further correlation to clarify the results on this subject.

Question 6. If one adds the number of replies to (a) and (b) of question 6, the general impression is favorable. The numbers answering item (c) of question 6 are large enough to warrant further study and correlation of these answers.

(Continued on page 56)

WELLSVILLE, NEW YORK. Sinclair Refining Company's new propane deresining unit at the Wellsville refinery, performs the dual role of removing undesirable asphaltic material from high quality Pennsylvania Grade lubricating oil and recovering heavy resins used in the manufacture of wax-coated paper and other everyday items. Fluor engineered and erected this plant on schedule and possesses the experience and ability to build processing units, large or small, anywhere in the world – not only for the refining industry but for natural gas, chemical, petrochemical, power and heavy industries as well.

BE SURE WITH **FLUOR**

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LOS ANGELES 22, CALIFORNIA

FOREIGN FACTS-FLUOR-PARIS
FLUOR OF CANADA-TORONTO
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ENGINEERS
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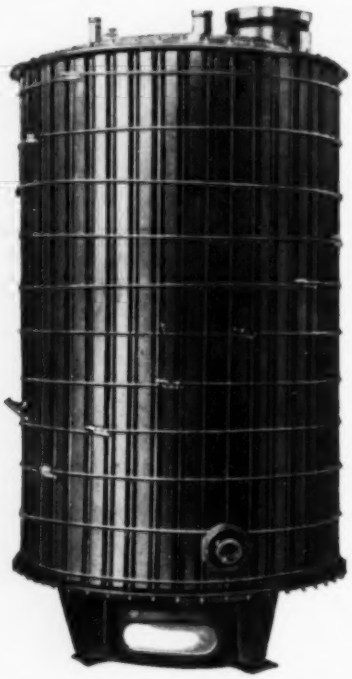
HOUSTON
BIRMINGHAM
TULSA

FOR BIG, CORROSION-RESISTANT TANKS

HAVEG IS A LOGICAL ANSWER...

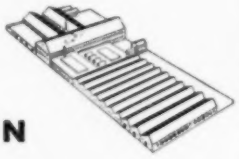


Get what you want with a Haveg-engineered tank. Haveg is not a lining or coating. It is a solid, non-metallic material (resistant to corrosion through and through) that is molded by the Haveg Corporation into tanks as large as 10 feet in diameter by 12 feet in depth. These are single piece, without seams or joints. By joining such sections, even larger tanks can be built. Low cost, with exceptionally long life.

From top to bottom, a Haveg tank has special design features to improve handling acids, bases, salts in your plant. Flat, sloping, cone, dished bottoms are molded to fit your drainage needs. Because Haveg can be machined and repaired on the spot, any change in piping is easily made by your own plant crew.

Work with a company that understands how to fight corrosion. Haveg has thousands of molds for any type of chemical handling equipment. Get the complete Haveg story by contacting your Haveg sales engineer and writing for a 64-page technical bulletin (F-6). It shows tank sizes, installation and machining tips, complete chemical resistance tables. Write now . . . for Haveg is a logical answer, both material and engineering-wise, for corrosion-resistant tanks, towers, pipes, valves, fittings.

The Haveg factory is at Marshallton, Delaware (phone Wilmington 3-8884). Capacity has been increased, with deliveries improved. Why take less, when you can get proven, long-life Haveg?



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SALES ENGINEERS: Atlanta • Chicago • Cincinnati • Cleveland • Detroit • Hartford
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NEWS

(Continued from page 26)

CHEMICAL INDUSTRY ON THE INCREASE

The number of chemical companies with securities listed on the New York Stock Exchange has increased 70% over the past quarter century, reflecting the dynamic competition existing in the industry, the Manufacturing Chemists' Association said recently. "In 1929, according to an Association spokesman, "there were forty-nine chemical manufacturing companies, with seventy-four security issues listed on the New York Stock Exchange. By 1939 the number of listed chemical companies had increased to sixty-three with eighty-nine issues of securities.

"By 1952 there were eighty-three chemical manufacturing companies with 128 separate issues of securities. The growth in chemicals assumes even more significance when it is realized that the total number of all companies listed on the New York Stock Exchange actually declined from 1419 to 1288 in the 1929-1953 period," it was pointed out.

ROHM & HAAS ADDS TO ACRYLIC MONOMERS

Rohm & Haas Co. has recently put into operation a new plant for the production of acrylic monomers, raw materials used in the manufacture of the company's plastic materials and other products. The new unit, which represents an $8,000,000 addition to the company's petrochemical operations at Deer Park, near Houston, Texas, employs, according to a recent report, an entirely new process using acetylene, carbon monoxide, and various alcohols.

Two years ago the company completed a plant at Deer Park for the manufacture of hydrogen cyanide.

NATIONAL DAIRY FORMS NEW SUBSIDIARY

A new subsidiary, Sheffield Chemical Company, Inc., has recently been announced by National Dairy Products Corp. This formalizes into a separate corporation the work carried on previously under the name of the Chemical Division of Sheffield Farms Company, Inc., National Dairy's Sealtest milk subsidiary.

With headquarters in Norwich, N. Y., Sheffield will manufacture products for use by the chemical, pharmaceutical, food, and other industries. At present the company distributes edible milk proteins, lactic acid, lactates, milk sugar, amino acids, bacterial nutrients used in producing antibiotics, etc.

PHILA.-WILMINGTON SECT. PLANS ONE-DAY MEETING

A one-day meeting, sponsored by the Philadelphia-Wilmington Section of the American Institute of Chemical Engineers and the University of Pennsylvania will be held on May 12, 1953, on the Penn campus in Philadelphia. Roy A. Kinckiner is general chairman for the meeting.

The general subject of the meeting will be "Chemical Engineering in the Process Industries." Speakers from eight different companies will discuss chemical engineering in all its phases with emphasis on their application to current operating processes, such as the production of hydrogen or phenol. It is expected to be of special interest to engineers who have been working in the chemical industry for five to ten years and to chemical engineering students.

In the evening, at a regular dinner meeting of the section, Chalmer G. Kirkbride, president, Houdry Process Corp., and vice-president of A.I.Ch.E., will give the after-dinner address. This meeting will also be the occasion for the presentation of the Zeisberg Award, given annually for excellence in report writing to senior chemical engineering students in colleges in the general area of the Philadelphia-Wilmington Section. The Zeisberg Award is offered in memory of the late Fred C. Zeisberg.

Details of the tchnical program follow:

Morning Session

PROCESS RESEARCH by G. Alex Mills, director, chemical research, Houdry Process Corp.

PROCESS DEVELOPMENT by James J. Hur, group leader, research, development department, Atlantic Refining Co.

PROCESS ENGINEERING by A. S. West, process design group leader, Rohm & Haas.

ECONOMIC ANALYSIS by Edwin M. Ott, manager, sales research department, Pennsylvania Salt Manufacturing Co.

Afternoon Session

PROJECT ENGINEERING by W. F. Cooke, assistant division engineer, design division, engineering department, Du Pont Co., Inc.

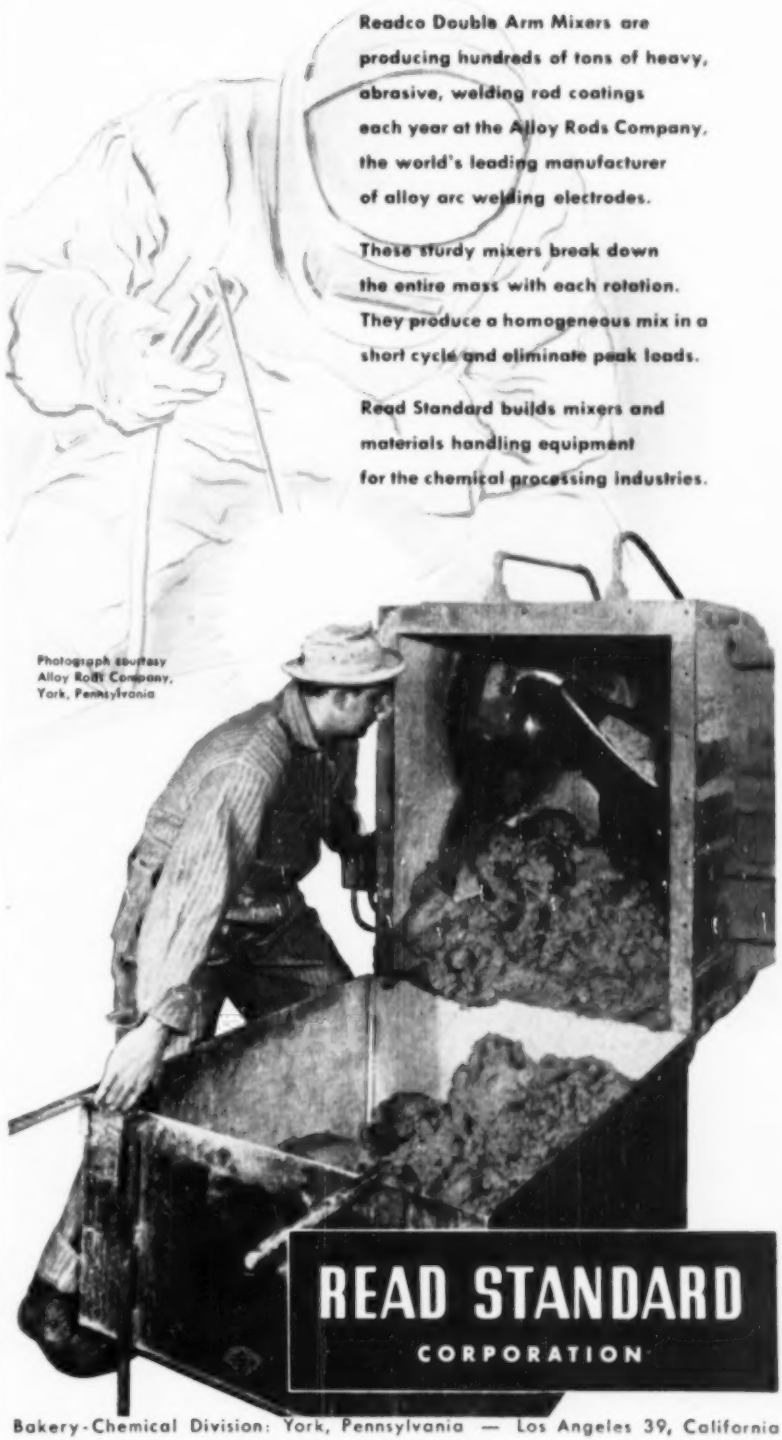
CONSTRUCTION ENGINEERING by G. L. Eaton, manager, process engineering division, United Engineers and Constructors, Inc.

OPERATIONAL ENGINEERING by W. C. Huffman, general foreman, aromatics production, Sun Oil Co.

MARKET RESEARCH ENGINEERING by R. E. Chaddock, manager, sales research division, Hercules Powder Co.

(More News on page 53)

only strong arm methods survive these tests



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Photograph courtesy Alloy Rods Company, York, Pennsylvania

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MARGINAL NOTES

News of Books of Interest to Chemical Engineers

Day-to-Day Data

Technical Data on Plastics. Manufacturing Chemists' Association, Inc. Washington, D. C. (1952). 181 pp. $2.50.

Reviewed by Raymond B. Seymour, Executive Vice-President, The Atlas Mineral Products Co., Mertztown, Pa.

This is a handy reference work including up-to-date values in tabular form for processing physical, electrical and mechanical properties of twenty different commercial plastics. A short discussion on composition, molding, properties and utility precedes each table. Trade names of the basic materials and addresses of manufacturers are included in each section.

The plastics discussed are primarily those produced by the twenty-nine members of the association, viz., urea-formaldehyde, melamine - formaldehyde, phenol formaldehyde, alkyds, silicones, epoxy resins, polyesters, acrylics, polyethylene, polytetrafluoroethylene, polyvinyl formal and butyral, vinyl chloride polymers and copolymers, vinylidene chloride, styrene, cellulose acetate, cellulose acetobutyrate, cellulose propionate, ethyl cellulose, cellulose nitrate and nylon.

Valuable graphical presentations showing the effect of temperature and humidity on specific mechanical properties are included in many chapters. The book also contains a chapter on foam plastics and films, a bibliography, and an index.

As might be expected, much of the data contained in this book can be found elsewhere. However, the data in the tables are authentic, accurate, up to date and well arranged in one handy volume. The book is inexpensive, well written and is recommended to those requiring technical data on plastics for engineering design.

Theory and Applications of Silicates

Soluble Silicates, Their Properties and Uses. James G. Vail. Reinhold Publishing Corp., New York (1952) Vol. I—357 pp., $9.00. Vol. II—669 pp., $15.00.

Those who use soluble silicates in large quantities, namely, the chemists, and technologists in the detergent, textile, and gel industries, will find both volumes of this work informative and applicable.

"Soluble Silicates" is one of a series of monographs sponsored by the American Chemical Society. The current work is a completely new writing and supplants a previous monograph by the same author, which has long been out of print.

Vol. I covers the chemistry and physical properties of the soluble silicates and such subjects as the history, manufacturing processes, commercial forms, methods of analysis, phase equilibria of anhydrous and hydrous systems. A valuable index and much illustrative material accompany the text.

Vol. II is concerned with the technical applications. Detailed sections deal with clay dispersion, clay washing, and the reclamation of lubricating oils. In this volume there is a review of silicate adhesives, and related problems, such as cements, soil stabilization and drilling muds.

Included is a discussion, in the chapter on sols and gels, on the preparation and use of sols in water clarification and of gels that are a base for catalysts. This volume is also replete with photographs and graphs.

Approximately 2,000 references add to the thoroughness of the work—three years were spent on its preparation—and facilitate an understanding and grasp of the importance of silicates. A feature not to be overlooked is the simplicity of the language, rendering background knowledge quite unnecessary.

Dr. Vail was retired vice-president of the Philadelphia Quartz Co., at the time of his death in December, 1951, and was considered the world's leading authority on this subject.

What's Your I. Q. on S. Q.?

A Guide to Sales Quota Setting. John E. Ullmann, Chemonomics, Inc., New York 17, N. Y. (1952) 63 pp., $3.00.

Reviewed by Francis J. Curtis, Vice-President, Monsanto Chemical Co., St. Louis, Mo.

This work gives an excellent general review of the subjects which should be of interest to chemical engineers interested in or engaged in the sales field and who expect eventually to get into sales management. It covers in a broad way the various methods in operation for setting sales quotas, a subject in which there is no particular degree of agreement among sales managers. The book presents the different methods objectively with some discussion of advantages and disadvantages.

There are some subjects which might well have been added, particularly a discussion on the moot question as to whether sales quotas should be set for a group of salesmen or for individuals, and in what industries. The review did question whether a strictly mathematical or cost approach to cutting off small orders is desirable. In the chemical industry particularly, many small orders are really trials for new developments that may well grow and become big. Obviously, the man in on the ground floor is going to have a much better position when the big orders come along. Likewise, a mathematical approach might lead to the refusal of small orders from large companies by order clerks with a considerable resultant loss of good-will and eventually big business.

The rather sticky question of how to handle house accounts, which are those obtained by top sales management but which must be serviced by field salesmen, and the somewhat similar problem where purchases are made in a central location such as New York or Chicago but delivery is made locally and serviced by field salesmen receive no attention. While these points may be small, they are difficult enough to have prevented many chemical companies from setting individual sales quotas.

All in all, however, the book may be commended as having the value of brevity and teaching what lines of attack could be profitably studied in greater detail.

Books Received

Photoconductivity in the Elements. T. S. Moss. Academic Press, Inc., New York (1952). x + 263 pp., $7.00.

Encyclopedia of Chemical Reactions. Vol V. Ed. C. A. Jacobson. Reinhold Publishing Corp., New York (1953). 787 pp., $15.00.

The Engine Indicator for Performance Evaluation. John D. Hines. Cooper-Bessemer Corp., Mount Vernon, Ohio (1952). 53 pp. $1.50.

Metadyne Statics. Joseph Maximus Pestarini. Technology Press of Massachusetts Institute of Technology and John Wiley & Sons, Inc., New York (1952). 415 pp. $9.00.

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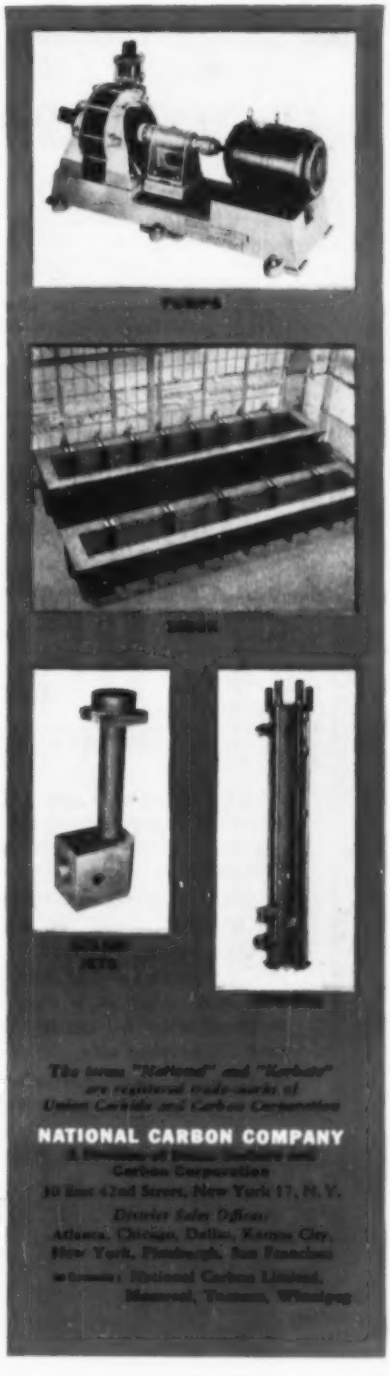

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These names are listed in accordance with Article III, Section 7, of the Constitution of A.I.Ch.E.

Objections to the election of any of these candidates from Active Members will receive careful consideration if received before May 15, 1953, at the Office of the Secretary, A.I.Ch.E., 120 East 41st, New York 17.

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Bryan, John L., Jr., *Baton Rouge, La.*
Cabala-Pavesi, Luciano, *Concepcion, Chile, S.A.*
Cavendish, S. G., *So. Charleston, W. Va.*
Claitor, L. C., *Jeannette, Pa.*
Clancy, Stephen M., *Portsmouth, Va.*
Costigan, James T., *New York, N. Y.*
Frahme, Herman H., *Akron, Ohio*
Freeland, Emile C., *New York, N. Y.*
Galt, John L., *Pittsfield, Mass.*
Gerke, R. P., *So. Charleston, W. Va.*
Green, Duane L., *Wilmington, Del.*
Greer, John Edwin, *Lawrence, Kan.*
Hainsworth, William R., *Los Angeles, Calif.*
Harte, Charles R., Jr., *Flossmoor, Ill.*
Holsinger, Fred J., *Argo, Ill.*
Hooker, Thomas, *Niagara Falls, N. Y.*
Johnsen, Knut J., *Parker, Pa.*
Keefer, Robert W., *Houston, Tex.*
Keppler, William E., *Bloomsburg, Pa.*
Kistler, S. S., *Salt Lake City, Utah*
Lautner, William K., *Nashville, Tenn.*
Leininger, Theodore L., *Charleston, W. Va.*
Lenoir, John M., *Fayetteville, Ark.*
Levin, Herman, *San Antonio, Tex.*
Logan, Robert L., *Geneva, Ill.*
Lowman, Malden C., Jr., *Emeryville, Calif.*
Miles, F. W., *Oak Ridge, Tenn.*
Mitchell, Thomas R., Jr., *Florence, Ala.*
Moxley, Charles J., *Baltimore, Md.*
Nason, B. Ross, *Boston, Mass.*
Northeimer, Evan S., *Charleston, W. Va.*
Parker, Harry H., *Chicago, Ill.*
Peet, N. P., *Baytown, Tex.*
Phillips, Weller A., *Baton Rouge, La.*
Pollak, Oscar L., *Kew Gardens, N. Y.*
Rand, William E., *Stanford, Calif.*
Revilock, Joseph F., *Bay Village, Ohio*
Rothe, Karl H., *Webster Groves, Mo.*
Ryan, Joseph R., *Kenmore, N. Y.*
Sacra, Charles F., *New Castle, Del.*
Shane, Presson S., *Augusta, Ga.*
Smith, Howard B,. Jr., *Drexel Hill, Pa.*
Tanner, H. M., *Baton Rouge, La.*
Tooker, John S., *Glen Oaks, Floral Park, N. Y.*
Truesdell, Dan A., *Houston, Tex.*
Wadsack, W. A., *Cuyahoga Falls, Ohio*

Applicants for Associate Membership

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Crump, Joseph R., *Houston, Tex.*
D'Amour, N. A., *Arvida, P.Q., Canada*
Main, Earl L., *Nixon, N. J.*
Margolis, Asher J., *Chicago, Ill.*
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Applicants for Junior Membership

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Barry, Arthur L., Jr., *Naugatuck, Conn.*
Bauman, Howard F., *Kingsport, Tenn.*
Black, Robert O., *Racine, Wis.*
Blaha, Richard J., *Mentor, Ohio*
Bollman, Robert N., *Cincinnati, Ohio*
Bradfute, John O., *Oak Ridge, Tenn.*
Brasie, William C., *Midland, Mich.*
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(Continued on page 42)

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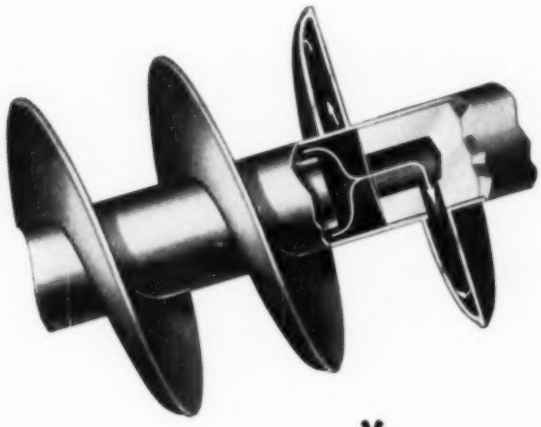

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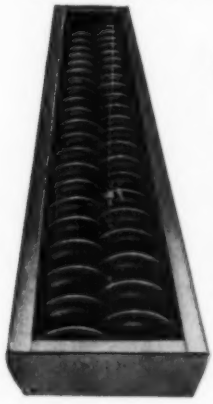

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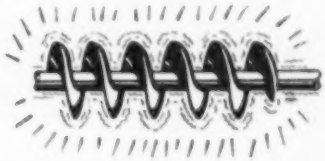

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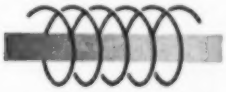

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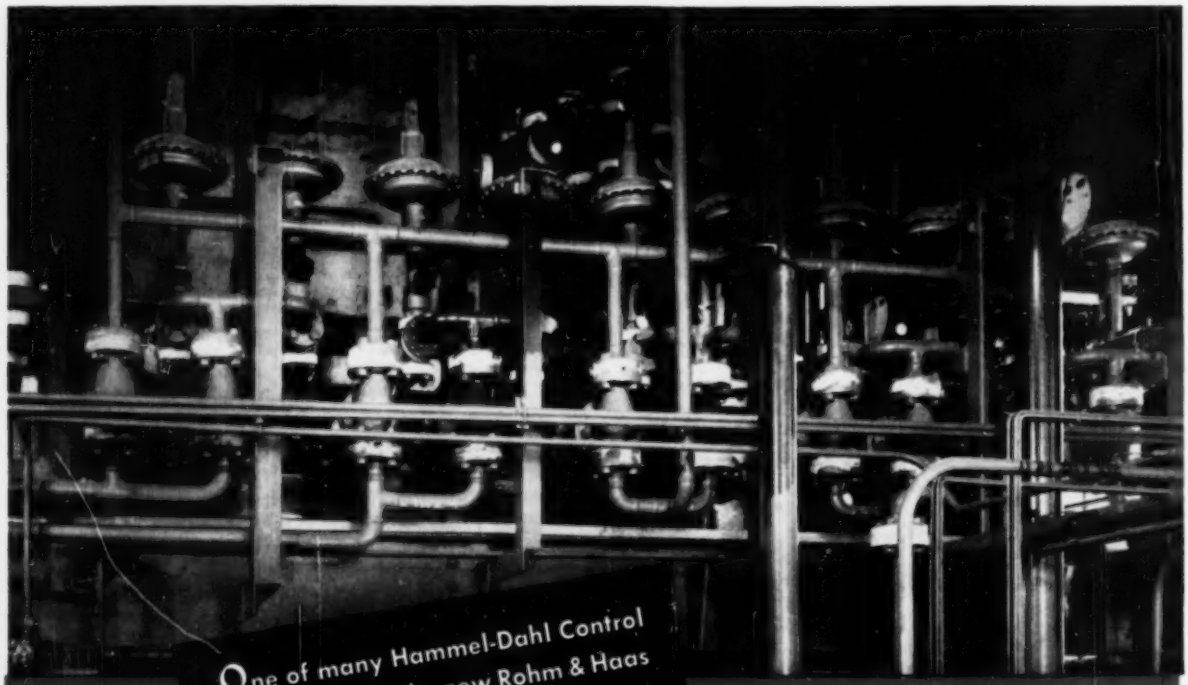

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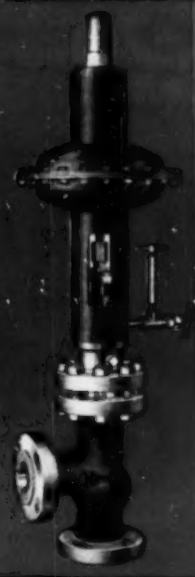

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18 • *PIPE LINE FILTERS.* Four small pipe line filters for installations requiring only 40 lb./sq.in. maximum pressure for compressed air or gas. From Dollinger Corp. Two sizes, 3½ in. diam., with lengths 6½ in. and 10 in. Absorption pad media removes oil and water vapor from lines.

19 • *SPECTROSCOPIC ELECTRODES.* Eleven preformed shapes of spectroscopic electrodes. Diagrams of each design in folder. National Carbon Co.

20 • *VALVE MATERIALS.* Added to Crane Co. line are several valve body, diaphragm, and lining materials. Valve bodies and disc-holders in variety of metals, and rubber linings. Special valves for vacuum, oxygen, acetylene service. Separate diaphragm and disc construction.

21 • *MOTORS.* Robbins & Myers, Inc. line of chemical plant motors from 1 to 40 hp. NEMA frames to 405. Available in totally enclosed and Underwriter's approved explosion-proof construction. Cast bronze, aluminum, and iron ventilating fans. Corrosion resistant.

22 • *MULTIPLE-ACTION SCRUBBER.* A Johnson-March Corp. system for control of stack dust from rotary dryers, cyclones, kilns, mixers; asphalt plant, chemical plant and other stacks. Requires 2 gal./min. water at 40 to 50 lb./sq.in. for each 1000 cu.ft. gas/min.

CHEMICALS

24 • *SULFUR HEXAFLUORIDE.* Technical service bulletin on sulfur hexafluoride from General Chemical Division, Allied Chemical & Dye Corp. Contains selected data on physical properties of SF_6. Available to research and production men.

25 • *FORMIC ACID.* Heyden Chemical Corp. technical bulletin on formic acid. Summarizes recent research on uses in textile, chemical, pharmaceutical industries. Considered are dyeing of nylon fabrics, formulations in vitamin production, sections on resins, solvents, fumigants, rubber, and perfumes.

26 • *DIMETHYL ISOPHTHALATE.* Now commercially available from Hercules Powder Co. dimethyl isophthalate. Material is isophthalic acid in its low-melting form, easily processed methyl ester. For preparing plasticizers, alkyds, polymers.

27 • *PHARMACEUTICAL CHEMICALS.* Dow Chemical Co. revised edition of catalog of pharmaceutical and fine chemicals. Contains additional data, product information including chemical name, formula, properties, solubilities. A handbook for research and production personnel.

28 • *SODIUM DISPERSIONS.* From Ethyl Corp., leaflet on sodium dispersions. Can be pulverized and used in air. Describes new organic reaction, illustrates advantages of use.

29 • *12-HYDROXYSTEARIC ACID.* Booklet from Emery Industries, Inc. covers 12-hydroxystearic acid and hydrogenated castor oil. Emphasizes potentialities for applications with unique chemical structures.

BULLETINS

30 • *CUT-OFF SAW.* Tri-Clover Machine Co. super-speed power cut-off saw for cutting tubing or pipe of any thickness. Portable, 6 in., 70 lb., 110-volt ac.

31 • *HOT OIL HEATING.* Industrial process heating by hot oil circulation, high temperature, low-pressure system by Parks-Cramer Co. A 64-page illustrated booklet covers details of operation and construction.

32 • *FLOTATION TECHNIQUES.* From the Tall Oil Assoc., bulletin No. 11 on use of tall oil in flotation processes. Covers principle, phosphate rock, manganese and iron ore flotation.

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33 • X-RAY INSPECTION. Inspection and examination of castings, weldings, foods, confections, crystal analysis, etc., by X-ray. General Electric bulletin describes procedure. Illustrated.

34 • THREAD COMPOUND. A Hi-Temp anti-seize thread compound of microflake copper particles in nonvolatile and viscous carrier. Permits parting of threaded assemblies of dissimilar alloys after exposure to high temperatures. Felt Products Mfg. Co.

35 • FLEXIBLE COUPLINGS. Complete line of flexible couplings by Lovejoy Flexible Coupling Co. described in bulletin. Illustrations, diagrams, tables of specifications and dimensions.

36 • MIX-MULLERS. Bulletin describes two high capacity mix-mullers. Simpson Mix-Muller Division, National Engineering Co. For mixing dry, semi-dry, and pasty materials. Used in chemical, ceramic, and food industries. Uses spring loaded muller for adjustment to various pressures and materials.

37 • DRYING SYSTEM. From Arnold Dryer Co. folder on Heil Ardriers used in production of dehydrated forage crops, by-products, industrial wastes, chemical residues. Features rapid evaporation, minimum retention in drying drum, accurate controls.

38 • COMPRESSORS. Spiraxial gas or air compressor addition to line of Roots-Connersville Blower Division of Dresser Industries, Inc. Features two intermeshing screw-rotors arranged to rotate in opposite directions. Flow of air or gas under compression is axial; permits large inlet opening; prevents strangulation of inlet air, and increases volumetric efficiency.

39 • BUTYL SEALS. Stainless fittings with butyl rubber seals announced by Cooper Alloy Foundry Co. Permit use of Quikpul installations under variety of corrosive conditions and services. Specially effective in sulfuric, hydrochloric, acetic acids and resistant to nitric and chromic acids.

40 • PNEUMATIC TRANSLATOR. For remote indicating, recording, control of pressure, flow, liquid level, pneumatic translator by Askania Regulator Co. Measures pressures to 3000 lb./sq.in., transmits air signals in range of 3 to 15 lb./sq.in. Accuracy within 0.5% of maximum at all ranges.

41 • PRESSURE FILTERS. Retractable shell-type pressure filters from Dravo Corp. For chemical, metallurgical, and allied industries. Welded steel construction, shell 14 ft. long, 60 in. diam. Head stationary and is breech-locked to shell by remote control.

42 • TWIN SHELL BLENDER. For drug and pharmaceutical industries where thorough blending is required. Dust control system prevents escape of dust to surrounding work areas during filling and emptying. Patterson-Kelley Co., Inc.

43 • CONCRETE HARDENER. Flexrock Co. folder on Flintcrust liquid, a flush-on preparation to prevent sanding, dusting, and break-up of heavily trafficked concrete floors.

44 • EXPANSION JOINTS. Redesigned Flexonics Corp. line of expansion joints. Catalog gives specifications and supporting data. Increased traverse per corrugation. Corrugated and convoluted types flexible metal hose.

45 • FREQUENCY COMPUTER. Developed to provide a simple and accurate frequency measuring unit for flow-metering system. Element generates electrical pulses with frequency proportional to flow rate. Ranges 5 to 100 cycles/sec., accuracy ±0.5% full scale. North American Instruments, Inc.

46 • STEAM GENERATOR. Bamag system high-pressure steam generators from General Industrial Development Corp. Closed circulation of steam and condensate. Operates at 700° F. Used with evaporating and distilling equipment in oils, varnish, fatty acid, tar plants. Flow diagrams.

47 • RESIN-BONDED FIBERGLAS. Chemically resistant products in-

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49 • LEFAX CATALOG. Lefax catalog listing more than 2000 pocket-size technical data books. Covers all branches of engineering.

50 • LABORATORY SAFETY. Fisher Scientific Co. leaflet "Safety in Today's Laboratory," illustrated with safety products and safeguard suggestions.

51 • CYLINDERS FOR POWER. Hanna Engineering Works bulletin describing how hydraulic or pneumatic cylinders are used to activate machines. Shows twenty-one application photographs. Also technical article on pneumatic and hydraulic drive.

52 • STEAM TUBE DRYER. Louisville steam tube dryer from General American Transportation Corp., for organic and inorganic materials. Bulletin shows schematic views, sizes and dimensions, complete description of parts, etc.

53 • RUBBER STOCK. Stalwart Rubber Co. line of rubber stock, including silicone rubber. Includes temperature, oil and gas, chemicals, abrasion and weather-resistant types. Details on applications, aging tables, other data.

54 • REGULATING VALVES. Double-seated rotary stem regulating valves from Brown Instruments Division, Minneapolis-Honeywell Regulator Co. For lever and weight actuation with plain or outboard bearing construction. Data sheet on size, construction, body-temperature ratings.

55 • PILOT PLANT FLASKS. Reaction flask with interchangeable heads, glass or stainless. Also reaction set-up with conventional flasks, large capacity, taper or spherical joints. Folder from Ace Glass, Inc.

56 • PURIFIERS. For cleaning up mist, dirt particles, and other entrainment in pipe-lines Hi-eF purifiers from V. D. Anderson Co. Used in the chemical, food, petroleum and other industries. Cutaway views, seven types.

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58 • INJECTION MOLDING. In information bulletin from Monsanto Chemical Co. techniques for molding styrene plastic-covered. Section on molds, materials, fillers, storage, preheating, degating.

59 • FILTERS. For use in the sugar industry Niagara Filter Corp. Auto-Sluice filters. On liquors of 65° Brix, rates of 4 to 5 gal./(hr.)(sq.ft.). Details of construction and operation, illustrations, etc.

60 • INDUSTRIAL FABRICS. A 24-page illustrated booklet from Wellington Sears Co. on industrial fabrics. Includes natural and synthetic fibers, illustrations of weaves, fabrics for coating, laminated plastics, filtration.

61 • RECORDERS AND CONTROLLERS. Catalog of pH and conductivity recorders and controllers from Brown Instruments Division, Minneapolis-Honeywell Regulator Co. Information on how and where to use automatic pH, Redox, and conductivity measuring and controlling equipment. Includes theory of electrochemical measurement.

62 • WELDED TANK CARS. Various tank cars by American Car and Foundry Co. Detailed sectional diagrams, capacities, weights, listed. Also describes manufacture of castings, pressings, processing equipment.

63 • DUST ELIMINATOR. Schmieg Industries, Inc. line of Centri-Merge dust and fume eliminators, swirl type, available in sizes 400 to 2500 cu.ft./min. Complete diagrams of each unit in bulletin.

64 • CONSTANT TEMPERATURE EQUIPMENT. Information on ovens, incubators, water heaters and thermoregulators, including details of operation and construction in Central Scientific Co. bulletin.

65 • VACUUM. Describing the use of vacuum in industry, a 12-page reprint from Ingersoll-Rand Co. Discusses method of making a vacuum. Two full-page charts on uses and manufacture.

66 • PUMPS. Centrifugal, reciprocating, screw, and rotary pumps of the Warren Steam Pump Co., Inc. Bulletin covers piping, suction lines, rotation, dismantling, and general information. Charts and illustrations.

67 • TUBING STEEL. From Babcock & Wilcox Co., Tubular Products Division, folder on Croloy 5 steel pipe and tubing. Includes condensed data on welding, heat treatment, creep strength, mechanical and physical properties. Composition is 4 to 6% chromium, ½% molybdenum. Corrosion resistant.

68 • SPRAY-DRYER. New with Bowen Engineering, Inc. spray-dryers using nozzle atomization. Interchangeable in one spray-drying installation are two types of atomization. Booklet available.

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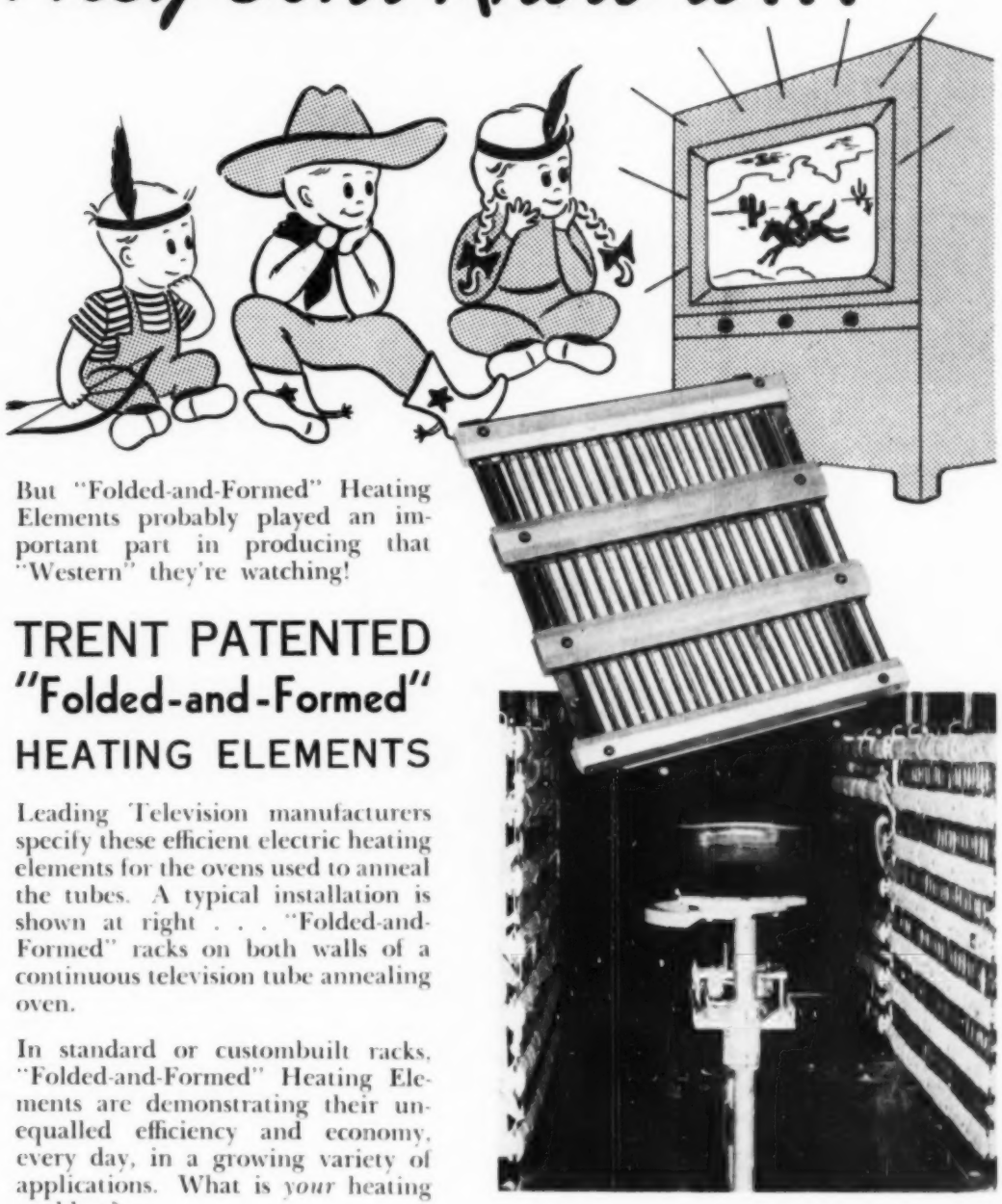

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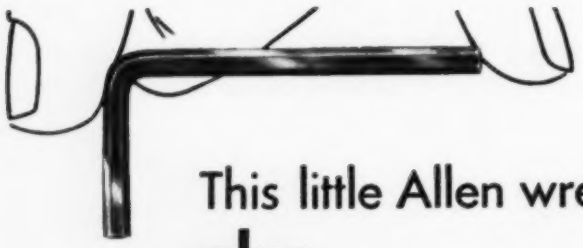

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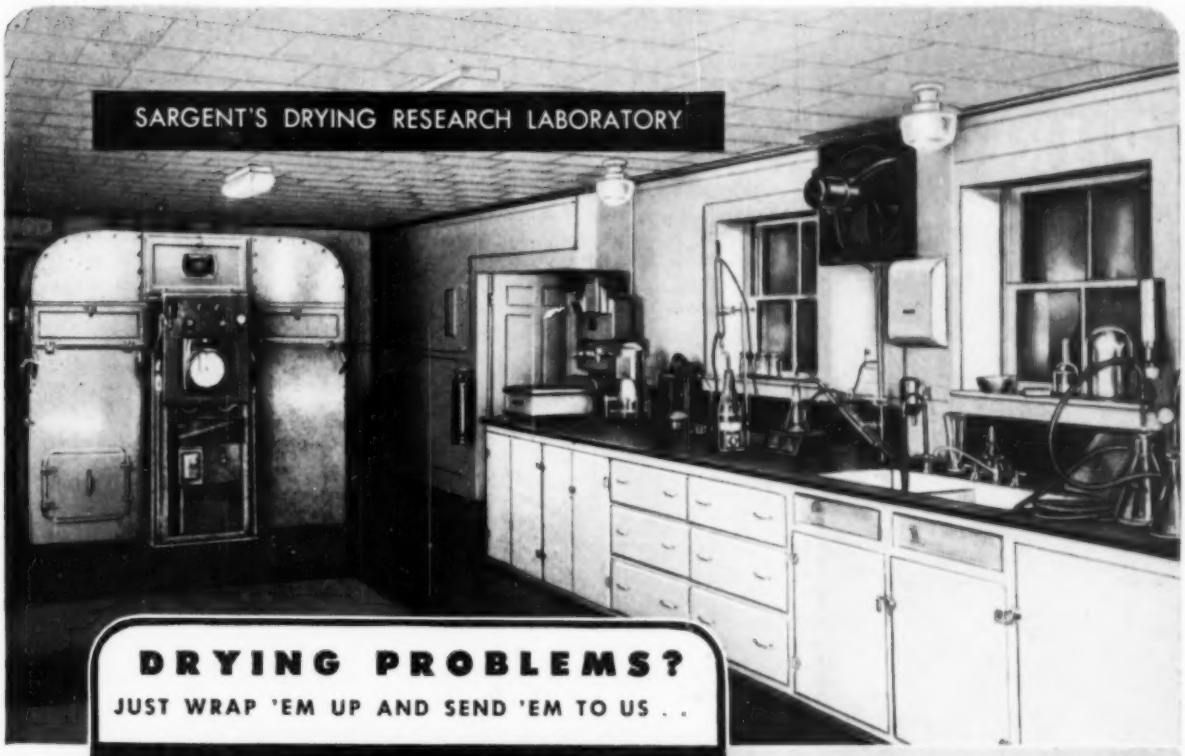
(*Continued on page* 48)



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2. Are you getting maximum rate of production possible, yet maintaining automatically controlled, unvarying quality?
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BILOXI MEETING

(Continued from page 22)

nomena experienced in other phases of mineral engineering were also discussed.

The adaptation of flotation and its principles to applications outside the mining industry was covered in papers by Dr. G. Gutzeit and Dr. R. B. Booth. Applications covered included.

1. Separation of ergot from rye.
2. Cleaning of foreign matter from vegetables prior to canning or freezing.
3. Removal of hulls from cereal grains.
4. Separation of proteins from natural products, for example, gluten from starch.

G. E. Montes, Ethyl Corp., who was on the Registration Committee; and H. J. Molaison, U. S. Southern Regional Lab., chairman, New Orleans Section, and co-vice-chairman, Biloxi meeting.

President W. T. Nichols and George Granger Brown.

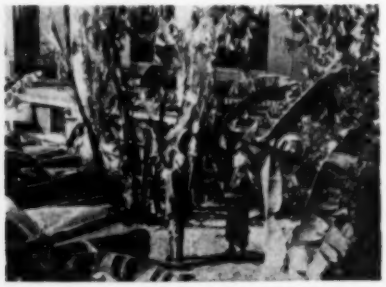
5. Separation of hydrophobic oils from cellulose and other carbohydrates.
6. Reclaiming of fibers and fillers from paper mill white waters and the de-inking of newsprint for re-use as paper raw material.
7. Separation of fat, oil and grease from waste liquors as the recovery of lanolin from wool scouring liquors.
8. Removal of organic contaminants from tank-car washings by the addition of certain floatable solids.
9. The separation of potassium salts from sodium salts by flotation.
10. Use of the flotation machine as both a clarifier and a degasifier, as practiced in the treatment of rayon spin baths to remove H_2S and colloidal sulfur.
11. The highly successful operation of the removing of grinding grit and metal contaminants from the soluble oil coolants used in the metal-working industry.
12. Use of the flotation machine as both a condenser and separator in the recovery of naphthalene, sulfur dioxide and water.

Dr. Gutzeit then proceeded to describe the laboratory procedures that should be used for flotation testing of chemical engineering problems. The paper showed how froth flotation might be helpful in at least five types of chemical engineering problems. The equipment required, reagents necessary and a test program were described by the author. The Gutzeit paper, in the opinion of the chairman of the symposium, Norman Morash, of the National Lead Co., will serve as a guide for all novices attempting to apply the flotation process to all problems.

To make the symposium complete for the engineer, costs were covered by Foster Crampton in his paper on cost estimating methods. During his talks he not only answered this question with regard to flotation but also brought in the other major items of equipment used by mineral engineers.

A discussion period was led by Dr. A. M. Gaudin. Dr. Gaudin first presented a short ultrahigh-speed film that showed the mechanism of bubble-particle attachment.

Speakers on the Sink and Float panel discussion, left to right: C. S. Westerberg, Link-Belt Co.; E. W. Gieseke; W. T. Turrall, Lehigh Navigation Coal Co., and panel leader; and, speaking, R. W. Hernlund, Western Machinery Co.



Mr. and Mrs. Philip Groggins admire a fine stand of bananas in front of the Buena Vista.

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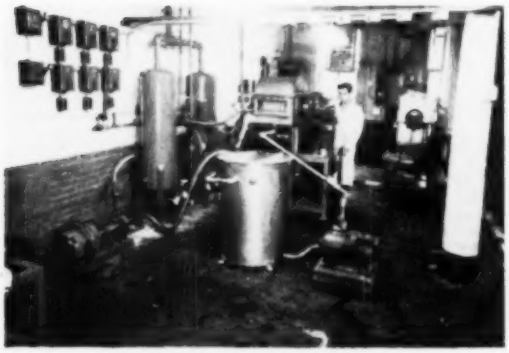

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3. Picking a manufacturer with the experience and Engineering ability for proper design;
4. Securing your filter from a manufacturer whose facilities for production are adequate to meet all requirements;
5. Picking a manufacturer with a trained and experienced service organization to make sure that the final installation meets the results which the test work indicated.

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3. Our Engineering Department is composed of well-informed designers and detailers with a world of field experience so essential in securing fool-proof, rugged design;
4. Our manufacturing facilities are by far the finest in the industry — almost half a million square feet of floor space with every needed modern tool to insure good, dependable construction;
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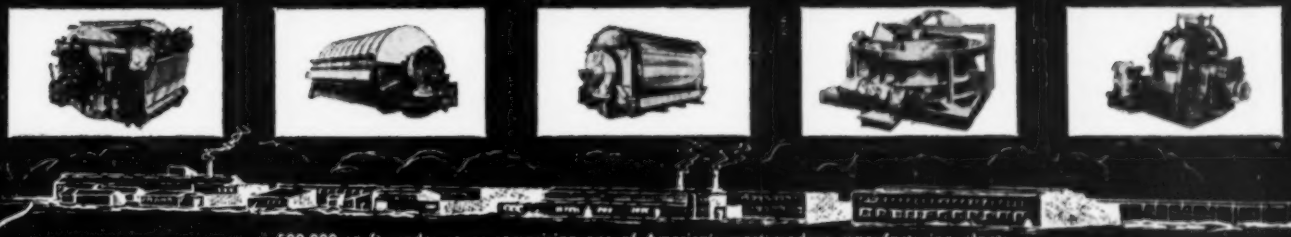

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	d. $3/year more	340
	e. $5/year more	332
10.	If you are a member of a Local Section, please check here	4953
	If you are not a member of a Local Section, please indicate the reason by checking only one of the following:	
	a. Commuting difficulties	908
	b. Have not been asked to join	251
	c. Am not interested	232
	d. Section dues are too high	27
	e. Don't like the group	16
	f. Don't know of a near-by local section	523
	g. No opinion	181
	h. Some other reason	554
11.	How active are you in your local section as measured by your average yearly attendance?	
	a. Have attended none of the meetings	2422
	b. Have attended about 25% of the meetings	2168
	c. Have attended about 50% of the meetings	995
	d. Have attended about 75% of the meetings	1068
	e. Have attended all of the meetings	303
12.	What is the main reason you attend the local section meetings? Please check the main reason only.	
	a. Interested in technical problems	1551
	b. Enjoy personal contacts and social gatherings	1701
	c. Feel it helps professionally	1492
	d. Enjoy extracurricular activities generally	306
	e. Some other reason	192
13.	What is the main reason for your missing local section meetings? Please check the main reason only.	
	a. Inadequate announcement	156
	b. Not member of a local section	1014
	c. Illness—self or family	149
	d. Not interested in program	1558
	e. Other engagements	3156
	f. Some other reason	935
14.	Do you wish that you had spent more time on liberal arts subjects at the expense of technical subjects in your academic work?	
	a. Yes	1976
	b. No	5347
	c. Undecided	418
15.	Do you feel you made the correct choice of career in becoming a chemical engineer?	
	a. Yes	6519
	b. No	422
	c. Undecided	808
16.	If you are an employee, does your employer recognize you as a professional man?	
	a. Yes	6484
	b. No	482
	c. Undecided	513
	d. Not an employee	231

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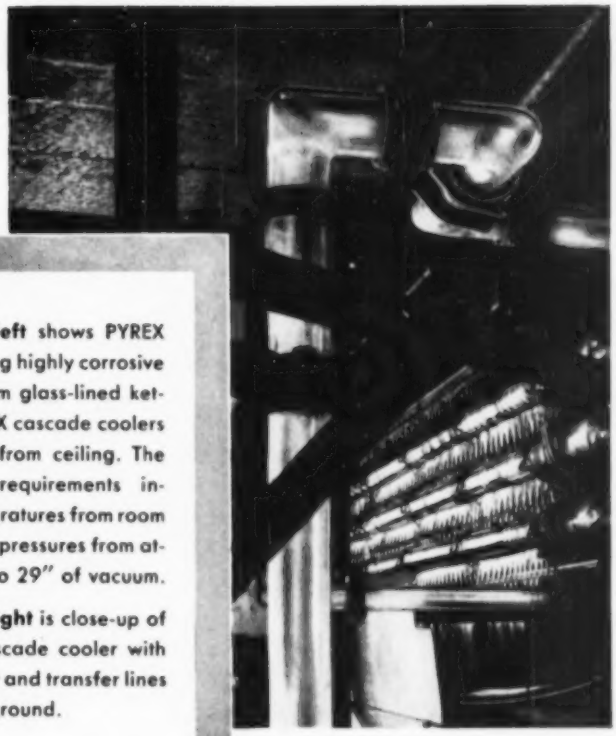

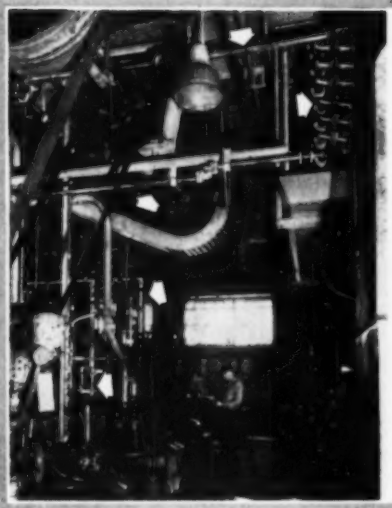

Photo on left shows PYREX pipe carrying highly corrosive solvents from glass-lined kettles to PYREX cascade coolers suspended from ceiling. The operating requirements include temperatures from room to 140° C.; pressures from atmospheric to 29" of vacuum.

Photo on right is close-up of another cascade cooler with glass supply and transfer lines in the foreground.

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- ☐ "Pyrex Cascade Coolers" (PE-8)

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CANDIDATES

(*Continued from page 42*)

Ornea, John C., *Emeryville, Calif.*
Osgood, Alain A., *Bedong, Kedah, Fed. of Malaya*
Paine, Albert E., *Cambridge, Mass.*
Pappas, S. G., *New York, N. Y.*
Patterson, Malcolm, *St. Albans, W. Va.*
Paul, James T., Jr., *Wilmington, Del.*
Perkins, J. H., Jr., *Philadelphia, Pa.*
Pike, John W., *Warren, Pa.*
Pokrivchak, George, *Hanover, N. J.*
Pratt, Stuart W., Jr., *Woodstown, N. J.*
Reed, Guy R., Jr., *Ft. Monmouth, N. J.*
Reeder, George Stuart, Jr., *Elkton, Md.*
Roeder, Gerald A., *St. Louis, Mo.*
Rogge, R. J., *Stamford, Conn.*
Sala, Louis M., *Louisville, Ky.*
Salisbury, Thomas E., *Akron, Ohio*
Savage, John L., *Akron, Ohio*
Sherman, Philip B., *Nyack, N. Y.*
Silberberg, Melvin, *Bayshore, L. I., N. Y.*
Spiller, Charles A., Jr., *Whiting, Ind.*
Stayton, Homer H., *Baytown, Tex.*
Stewart, Robert S., *Hatboro, Pa.*
Teschner, Charles L., *Cuyahoga Falls, Ohio*
Tesoro, R., *New York, N. Y.*
Thompson, Edward T., *New York, N. Y.*
Truesdell, Galen A., Jr., *Torrance, Calif.*
Valji, S. E., *Chicago, Ill.*
Vela, M. A., Jr., *Bartlesville, Okla.*
Watts, Admiral A., *Alhambra, Calif.*
Wehe, Albert H., *Baton Rouge, La.*
Wells, Harold N., *Sheffield, Ala.*
Whittington, David K., *Port Arthur, Tex.*
Wikman, Andrew O., *Baton Rouge, La.*
Wilson, Thomas R., Jr., *Idaho Falls, Idaho*

Secretary's Report

S. L. TYLER

The Executive Committee met at the Buena Vista, Biloxi, Miss., March 8, 1953, and received and approved Minutes of the meeting of Jan. 16, 1953, and the actions taken by mail in February, 1953. All those whose names appeared in the February issue of "C.E.P." as candidates for membership were elected to the grades indicated. There were 157 applicants elected to Student membership.

Six members were placed on the Suspense List because of their entering the Armed Forces and four members were reinstated to full participating membership status as they had returned from the Service. The election of nine applicants for Junior membership was rescinded because of nonacceptance.

M. C. Molstad was appointed the second representative of the Institute along with W. T. Dixon, who had been previously appointed to attend the meeting of the American Academy of Political and Social Science, April 10 and 11, at

(*Continued on page 52*)

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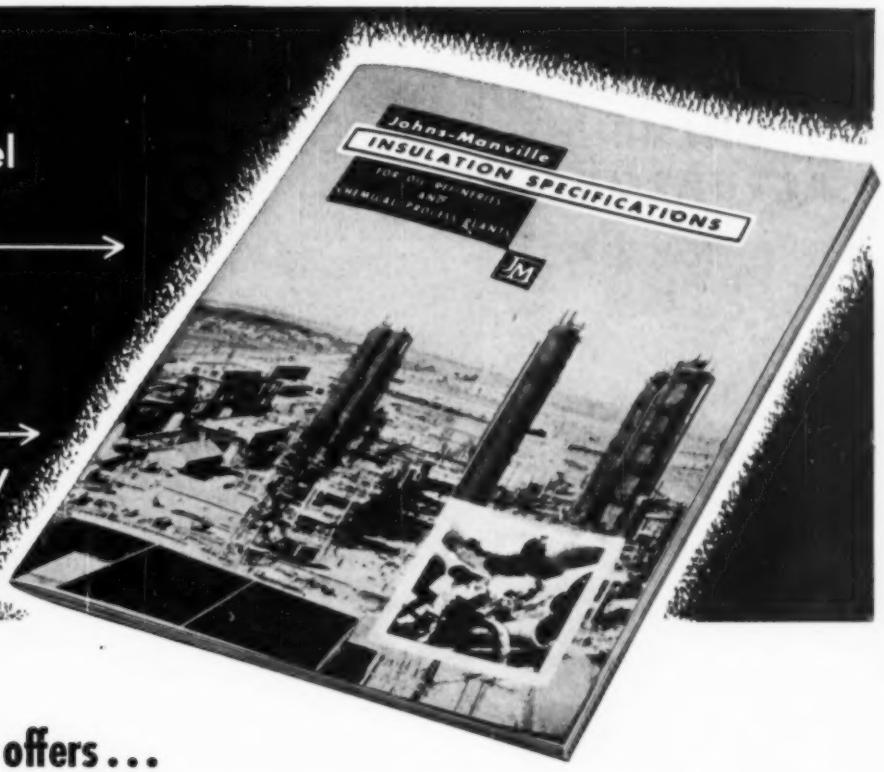

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FUTURE MEETINGS AND SYMPOSIA OF A.I.Ch.E.

Chairman of the A.I.Ch.E. Program Committee
Loren P. Scoville, Jefferson Chemical Co., 260 Madison Ave., New York 16, N. Y.

MEETINGS

San Francisco, Calif., Fairmont Hotel, Sept. 13-16, 1953.
Technical Program Chairman: R. W. Moulton, Head, Dept. of Chem. Eng., University of Washington, Seattle, Wash.

Annual—St. Louis, Mo., Hotel Jefferson, Dec. 13-16, 1953.
Technical Program Chairman: R. M. Lawrence, Monsanto Chem. Co., St. Louis 4, Mo.

Washington, D. C., Statler Hotel, March 8-10, 1954.
Technical Program Chairman: George Armistead, Jr., Consult. Chem. Eng., George Armistead & Co., 1200 18th St. N.W., Washington 6, D. C.

Springfield, Mass., Hotel Kimball, May 16-19, 1954.
Technical Program Chairman: E. B. Fitch, Asst. to Res. Dir., The Dorr Co., Westport, Conn.

Ann Arbor, Mich., Univ. of Mich., Ann Arbor, Mich. June 20-25, 1954—Conference on Nuclear Engineering.
Technical Program Chairman: D. L. Katz, Chairman, Dept. of Chem. and Met. Eng., Univ. of Mich., 2028 E. Eng. Bldg., Ann Arbor, Mich.

Glenwood Springs, Colo., Hotel Colorado, Sept. 12-16, 1954.
Technical Program Chairman: Prof. C. H. Prien, Dept. of Chem. Eng., Univ. of Denver, Denver 10, Colo.

Annual—New York, N. Y., Statler Hotel, Dec. 12-15, 1954.
Technical Program Chairman: G. T. Skaperdas, Assoc. Dir., Chem. Eng. Dept., M. W. Kellogg Co., 225 Broadway, N. Y. 7, N. Y.
Asst. Chairman: N. Morash, Titanium Div., National Lead Co., P. O. Box 58, South Amboy, N. J.

SYMPOSIA

Ion Exchange
Chairman: N. R. Amundson, Dept. of Chem. Eng., Univ. of Minnesota, Minneapolis 14, Minn.
Meeting—San Francisco, Calif.

Mixing
Chairman: J. H. Rushton, Dept. of Chem. Eng., Illinois Inst. of Tech., Chicago, Ill.
Meeting—San Francisco, Calif.

Transport Properties
Chairman: J. L. Franklin, Res. Assoc., Humble Oil & Refining Company, Baytown, Texas
Meeting—San Francisco, Calif.

Applied Thermodynamics
Chairman: W. C. Edmister, Calif. Res. Corp., 576 Standard Ave., Richmond, Calif.
Meeting—San Francisco, Calif.

Fluid Mechanics
Chairman: R. W. Moulton, Head, Dept. Chem. Eng., Univ. of Washington, Seattle, Wash.
Meeting—San Francisco, Calif.

Distillation
Chairman: D. E. Holcomb, Dean of Eng., Texas Technological College, Lubbock, Tex.
Meeting—St. Louis, Mo.

Dust and Mist Collection
Chairman: C. E. Lapple, Dept. of Chem. Eng., Ohio State University, Columbus 10, Ohio.
Meeting—St. Louis, Mo.

Drying
Chairman: L. E. Stout, Dept. of Chem. Eng., Washington University, St. Louis 5, Mo.
Meeting—St. Louis, Mo.

Use of Computers in Chemical Engineering
Chairman: John R. Bowman, Head, Dept. of Res. in Phys. Chem., Mellon Institute of Industrial Research, Pittsburgh 13, Pa.
Meeting—St. Louis, Mo.

Heat Transfer
Chairman: D. L. Katz, Chairman (Address: See Ann Arbor Meeting).
Meeting—St. Louis, Mo.

Carbonization
Chairman: R. S. Rhodes, Asst. Mgr., Prod. Dept., Koppers Co., Inc., Koppers Bldg., Pittsburgh 19, Pa.
Meeting—St. Louis, Mo.

Industrial Waste Disposal
Chairman: R. D. Hoak, Sr. Fellow, Mellon Inst., Pittsburgh 13, Pa.
Meeting—St. Louis, Mo.

Nuclear Engineering
Chairman: D. L. Katz, Chairman (Address: See Ann Arbor Meeting).
Meeting—Ann Arbor, Mich.

Reaction Kinetics
Chairman: N. R. Amundson, Dept. of Chem. Eng., Univ. of Minnesota, Minneapolis 14, Minn.
Meeting—New York, N. Y.

Liquid Entrainment and Its Control
Chairman: H. E. O'Connell, Ethyl Corp., P. O. Box 341, Baton Rouge, La.

Absorption
Chairman: R. L. Pigford, Div. of Chem. Eng., Univ. of Delaware, Newark, Del.

Authors wishing to present papers at a scheduled meeting of the A.I.Ch.E. should first query the Chairman of the A.I.Ch.E. Program Committee, Loren P. Scoville, with a carbon copy of the letter to the Technical Program Chairman of the meeting at which the author wishes to present the paper. Another carbon should go to the Editor, F. J. Van Antwerpen, 120 East 41st Street, New York 17, N. Y. If the paper is suitable for a symposium, a carbon of the letter should go to the Chairman of the Symposia, instead of the Chairman of the Technical Program, since symposia are not scheduled for any meeting until they are complete and approved by the national Program Committee. Before authors begin their manuscripts they should obtain from the meeting Chairman a copy of the Guide to Authors, and a copy of the Guide to Speakers. The first book covers the preparation of manuscripts, and the second covers the proper presentation of papers at A.I.Ch.E. meetings. Presentations of papers are judged at every meeting and an award is made to the speaker who delivers his paper in the best manner. Winners are announced in *Chemical Engineering Progress*, and a scroll is presented to the winning author at a meeting of his local section. Since five copies of the manuscript must be prepared, one should be sent to the Chairman of the symposium and one to the Technical Program Chairman of the meeting, or two to the Technical Program Chairman if no symposium is involved and the other three copies should be sent to the Editor's office. Manuscripts not received 120 days before a meeting cannot be considered.

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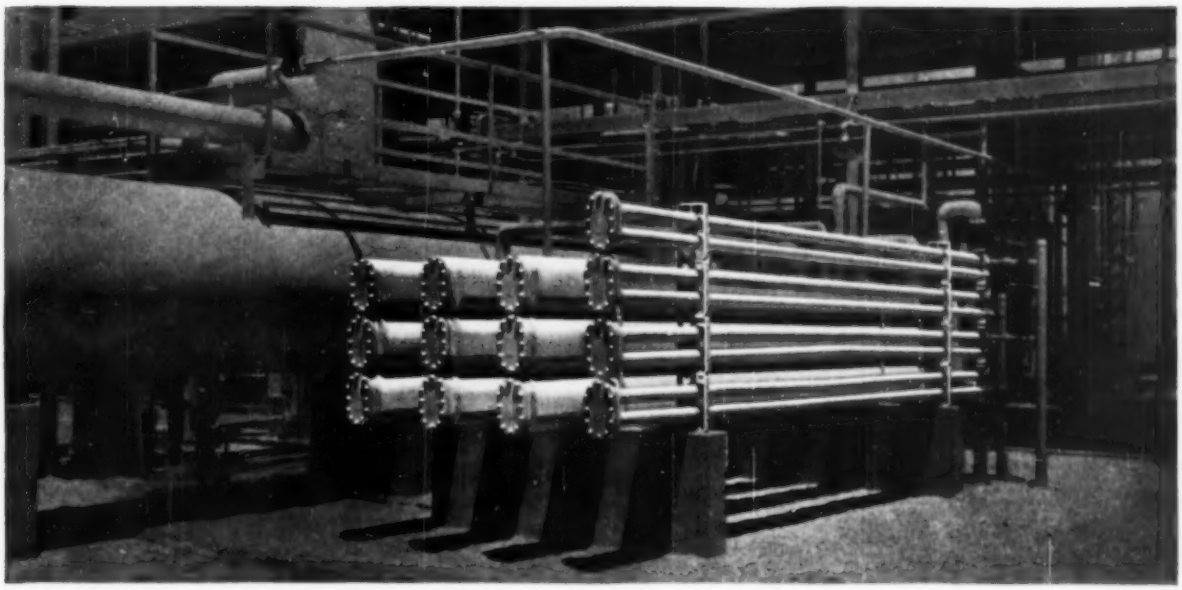

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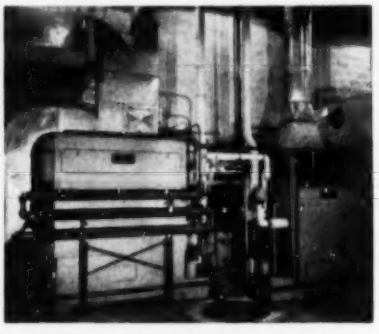

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SECRETARY'S REPORT

(*Continued from page* 48)

Philadelphia. R. N. Maddox was appointed counselor of the student chapter at Oklahoma A. & M. College to succeed L. N. Bartlett.

The Council of the Institute met at the Buena Vista, Biloxi, March 8, 1953, and after approval of Minutes, receipt of Treasurer's report, etc., proceeded to the new business.

A special subcommittee of the Public Relations Committee presented a preliminary report on the initial analysis of the Questionnaire. No conclusive results were reported; hence, no further information is available at this time. The analysis is being continued and reports will be forthcoming at as early a date as possible.

Council approved a contribution of $200 as part of the fund given by the member societies of the Engineers' Council for Professional Development toward a total fund of $6,000. The fund is being raised for a study of engineering curricula in the United States by the Committee on Evaluation of Engineering Education of the American Society for Engineering Education.

T. H. Chilton presented a report on recent developments in the formation of Engineers and Scientists of America, a new grouping of engineering and technical personnel, and as a result of his report the following action was taken:

> ***VOTED,*** **That the representatives of the A.I.Ch.E. on E.J.C. be instructed to present a resolution, to be referred to the Council for consideration by the constituent societies, with the recommendation of its adoption, declaring in effect that the enhancement of the status of the engineer is best promoted by his reliance upon his personal professional growth and accomplishment, and that his status as a professional man is endangered by reliance upon group efforts to act on his behalf in reaching short-range economic objectives; while at the same time the corresponding obligation is laid upon the employer of engineers to give each professional employee his due individual recognition as a member of a profession.**

President Nichols was authorized to appoint a subcommittee to keep in touch with developments and report periodically to the Council.

Secretary reported that it had been necessary to change the dates of the national meeting in Springfield, Mass., from May 9-12, to May 16-19, 1954, and this change was approved.

The Program Committee had recommended that approval be given to a Joint Heat Transfer Symposium with the Heat Transfer Division of A.S.M.E. to be held during the annual meeting in New York in December, 1954. This recommendation was approved.

The Program Committee further recommended that the Institute join with the Instrument Society of America in sponsoring a symposium on Instrumentation to be presented at the First International Instrument Congress and Exposition in September, 1954. This recommendation was also approved.

The recommendation of the Program Committee that a national meeting be held in Louisville, Ky., probably in March, 1955, was approved with the dates to be determined later.

Interim progress reports were received from several members of Council on behalf of the committees for whom they are acting as liaison representatives.

Lee Van Horn was appointed to represent the Institute at the inauguration of Raymond B. Allen as chancellor of the University of California at Los Angeles on March 20, 1953, and Charles R. Nelson was appointed representative of the Institute at the inauguration of Clark Kerr as chancellor at the University of California, Berkeley, on March 23, 1953.

Upon recommendation of the Executive Committee it was voted to credit to the Institute Meetings Account the surplus from the annual meeting in Cleveland in the amount of $2,735.96.

FELLOWSHIPS AT OKLAHOMA UNIVERSITY

Seven fellowships are now available in the school of chemical engineering at the University of Oklahoma. They are the following:

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Gulf Oil Corp.
Magnolia Petroleum Co.
The Texas Co.
Maloney-Crawford Tank and Manufacturing Co.
The Dow Chemical Co.

Details about these fellowships can be obtained by writing R. L. Huntington, chairman of the school of chemical engineering, University of Oklahoma, Norman, Oklahoma. Application blanks will be mailed promptly to anyone who is interested.

A.S.E.E. CONVENTION AT UNIV. OF FLORIDA

The 61st annual convention of the American Society for Engineering Education will be held next June 22-26 inclusive at the University of Florida in Gainesville. This year's host institutions—the University and the State of Florida—are arranging a technical and recreational program.

In addition to a technical program in the field of engineering education, attention will be given to the currently vital problems of manpower utilization and industrial expansion.

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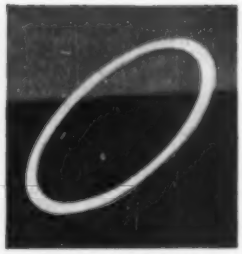

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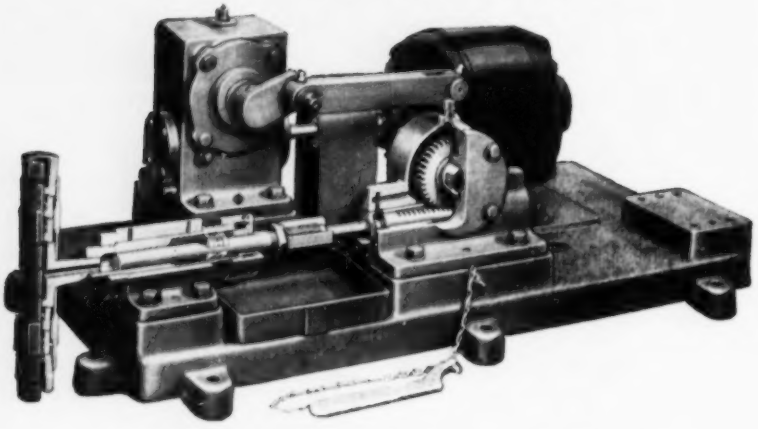
GARLOCK® PACKINGS, GASKETS, OIL SEALS, MECHANICAL SEALS, RUBBER EXPANSION JOINTS

For precisely controlled metering and proportioning of small volume flows...

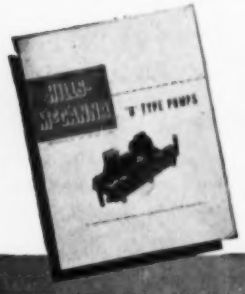


...the HILLS-McCANNA "U" Type Proportioning Pump

• The Hills-McCanna "U" Type Pump is designed to continuously meter and proportion small flows of the order of 0.10 to 24 gallons per hour per feed. Its accuracy and reliability suit it for research, pilot plant operation and full scale processing alike. The "U" type pump is suitable for batch or continuous operations.

Typical examples of "U" type pump applications include:

- Continuous addition of air entraining agents during cement manufacturing operations.
- Continuous injection of internal phosphate treatment and sodium sulphite oxygen scavenging in boiler plant water treatment.
- Injection of gasoline gum inhibitors into finished gasoline.
- Proportioning low molecular weight polymers and catalyst solution in resin research.



The new "U" Pump Catalog, UP-52, gives full information on the "U" type pump plus extensive application data including specific service recommendations for handling over 300 substances. Write for your copy, today. HILLS-McCANNA CO., 2438 W. Nelson St., Chicago 18, Ill.

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metering and proportioning pumps

Also Manufacturers of: Saunders Patent Diaphragm Valves

Force Feed Lubricators • Magnesium Alloy Sand Castings

INTERNATIONAL NUCLEAR ENERGY WEEK IN 1954

Plans for an international meeting to explore the chemical engineering aspects of nuclear processes are being forwarded by the A.I.Ch.E. Committee on Nuclear Energy, headed by D. L. Katz, chairman of the Department of Chemical Engineering, University of Michigan. The week-long meeting is tentatively scheduled for June 20 to 25, 1954, at Ann Arbor. Experts from all over the world will be invited to attend.

The program, which is expected to be the most comprehensive ever held on the subject, will begin with an all-day conference on educational problems associated with training engineers for the nuclear field. A two-day program will cover the design of nuclear power reactors, and there will be technical discussion of fuel resources, fuel preparation, chemical processing of spent fuel, disposal of radioactive products, use of isotopes, safety, instrumentation, and control and a conference on the social impact of the atomic age. Host for the meeting will be the Detroit Section, and R. R. White of the University of Michigan will be General Chairman.

Together with the Nuclear Energy Committee, two members of the Atomic Energy Commission Staff, Dr. Alberto F. Thompson and Dr. James G. Beckerley, are participating in plans for the program.

ENGINEERING IS CHIEF RED STUDY

Twenty-four of every twenty-five students beginning a university course in Communist China in 1952 are being prepared to contribute to China's industrialization program, according to a Herald-Tribune (New York) article reprinted by the Engineers Joint Council. "By far the heaviest enrollment is in engineering colleges," the article states, and "only about 3% of [the] year's university enrollment were permitted to take courses in the fine arts, law or political science."

"Accordingly," the article continues, "most Chinese universities or colleges have become advanced trade schools or technical colleges. Typical are the Peking Iron and Steel Academy, the Nanking Engineering College, and the Peking Academy of Mechanized Agriculture." An example of "the new type of university . . . is Tsinghua, in Peking, which for the last fifty years has been one of the nation's most respected and best known places of learning. Tsinghua reopened recently following reorganization, with an enrollment of 6,000 students. It is now a polytechnic institute, offering such courses as power-plant engineering, metal processing and petroleum engineering."

CONFERENCE SET ON ODORS IN INDUSTRY

A Conference on Basic Odor Research Correlation will be held under the joint sponsorship of the American Society of Heating and Ventilating Engineers and the New York Academy of Sciences on Thursday and Friday, April 23 and 24, 1953, at the Barbizon-Plaza Hotel, West 58th Street at 6th Avenue, New York. Papers to be presented at the morning and afternoon sessions will come under the general headings of "The Odor Problem in Industry and Sciences"; "The Olfactory Process, Status of Present Knowledge"; "The Status of Subjective and Objective Measurement Techniques"; and "Experimental Studies in Odor."

DOW TO PRODUCE POLYETHYLENE HERE

The Dow Chemical Co. is entering the production of polyethylene, according to a recent announcement. Negotiations for patent licenses and technical knowledge have been made with Imperial Chemical Industries, Ltd., a British firm. Dow's Texas Division at Freeport will construct plant facilities and expects to start production of this plastic in 18 to 24 months.

Among major uses of the plastic is film for packaging purposes, such as refrigerator food-storage bags; for shower curtains; and for drapery materials.

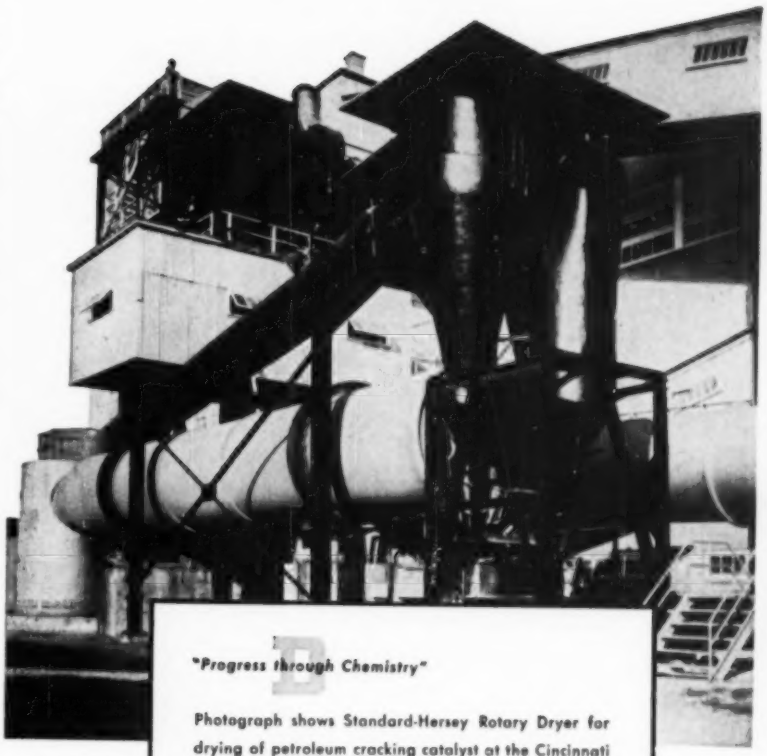
It is also used for many injection-molded articles—such housewares as food-storage dishes, mixing bowls, etc.—and for paper coating, plastic pipe, and wire and cable coating.

ELECTRON MICROSCOPE SUMMER STUDY COURSE

The annual Cornell University summer laboratory course in Techniques and Applications of the Electron Microscope will be given from June 15 to June 27, 1953, by the Laboratory of Electron Microscopy in the department of engineering physics. Under the direction of Dr. Benjamin M. Siegel, the course will have Dr. James Hillier of the RCA Laboratories, Princeton, N. J., and Dr. C. E. Hall of M.I.T., Cambridge, Mass., as guest lecturers.

It is designed for those research workers, institutional and industrial, who have recently entered the field of electron microscopy; also those who are now planning to undertake research problems involving applications of this instrument.

Inquiries should be addressed to Dr. Benjamin M. Siegel, Department of Engineering Physics, Rockefeller Hall, Cornell University, Ithaca, N. Y.



"Progress through Chemistry"

Photograph shows Standard-Hersey Rotary Dryer for drying of petroleum cracking catalyst at the Cincinnati Plant of The Davison Chemical Corporation. Patented Standard-Hersey intermediate-feed system makes the unit in reality a combination flash and rotary dryer with most desirable characteristics of each.

THE DAVISON CHEMICAL CORPORATION

CHOOSES

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STANDARD 50 YEARS 1902 1952 STEEL CORPORATION

Write today for complete, illustrated dryer Bulletin No 531, describing latest "PILOT" drying techniques and the more than 30 types of Standard-Hersey dryers for every process industry need.

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TABLE 2.—(*Continued*)

Question No.	Description	Total Received
17.	For use in correlating your replies we need some information about you. First, about your education; please check here only the highest degree you obtained.	
	a. None	73
	b. Undergraduate degrees, A.B., B.S., B.Ch.E., B.E., etc.	4132
	c. Master's, Professional, or equivalent, M.S., Ch.E., etc.	2298
	d. Doctorate, Ph.D., Sc.D., etc.	1229
18.	How many years have elapsed since your undergraduate degree was awarded? (As of December, 1952). Please check on appropriate line, rounding off a fraction of a year to the nearest whole number. (If you do not have an undergraduate degree please check number of years in the profession.)	
	a. Less than one	134
	b. 1 or 2	516
	c. 3 or 4	844
	d. 5 or 6	615
	e. 7 or 8	449
	f. 9 or 10	1170
	g. 11 to 15	1837
	h. 16 to 20	903
	i. 21 to 25	519
	j. 26 to 30	341
	k. 31 to 40	341
	l. Over 40	110
19.	Please indicate date of birth.	
	a. 1930 or later	96
	b. 1928–1929	305
	c. 1926–1927	483
	d. 1924–1925	705
	e. 1922–1923	917
	f. 1920–1921	1082
	g. 1915–1919	1895
	h. 1910–1914	923
	i. 1905–1909	515
	j. 1900–1904	338
	k. 1890–1899	416
	l. Before 1890	117
20.	Current data on your annual professional income (excluding income from investments or other sources) will give valuable and useful information when correlated with questions 17-19. Remembering that this questionnaire is anonymous, please check in the appropriate box. If you prefer not to answer this question, you may check "no answer" and continue with the balance of the questionnaire:	
	a. Under $4,000	173
	b. $4,001 to $5,000	685
	c. $5,001 to $6,000	1131
	d. $6,001 to $7,000	1138
	e. $7,001 to $8,000	1076
	f. $8,001 to $9,000	797
	g. $9,001 to $10,000	635
	h. $10,001 to $15,000	1264
	i. $15,001 to $25,000	504
	j. $25,001 to $50,000	209
	k. Over $50,000	34
	l. No answer	132
21.	What is your present grade of A.I.Ch.E. membership?	
	a. Active	2956
	b. Associate	459
	c. Junior	4324
22.	Are you a Registered Professional Engineer?	
	a. Yes, in one state only	2087
	b. Yes, in more than one state	270
	c. No	5418
23.	If the answer to Question 22 is "yes," do you feel this has been of importance to you in your work?	
	a. Yes	577
	b. No	1631
	c. Undecided	246
24.	If the answer to Question 22 is "no," are you registered as an Engineer in Training?	
	a. Yes	441
	b. No	5032
25.	If the answer to Question 22 is "no," is it your intention to become a registered engineer?	
	a. Yes	1440
	b. No	2305
	c. Undecided	1485
26.	What is your occupation? This question is intended to classify broadly your activities according to your main field of endeavor, or major function. Please check one only.	
	a. Research and development	2525
	b. Design (process, plant, mechanical engineering, drafting, etc.)	1152
	c. Plant operation, construction, tech. services, maintenance, equipment, production	1806
	d. Teaching, education	365
	e. Consulting	196
	f. Economics, market analysis, purchasing, financial, etc.	164
	g. Sales (development, technical, advertising, etc.)	389
	h. Placement, training or employee, labor or public relations	31
	i. Management	865
	j. Special services, such as patents, library, literature research, safety, etc.	67
	k. Other unlisted fields	162
27.	What is your relationship to your main business? Please check one only.	
	a. Self-employed	103
	b. Employee of:	
	1. Private firm or corporation	6064
	2. Federal Government, state gov't or other public authority	294
	3. Educational institution	968
	c. Member of Armed Forces	281
	d. Student	85
	e. Retired	53
	f. Unemployed	31
	g. Other	24
28.	How many professional or technical people are employed in your company or organization?	
	a. Less than 10	479
	b. 10 to 100	1158
	c. 101 to 1,000	3066
	d. Over 1,000	2981
29.	Are you, or have you been, an Officer, Director or committee member in the National A.I.Ch.E.?	
	a. Yes	502
	b. No	7257
30.	Are you, or have you been, an officer or committee member in your local section?	
	a. Yes	1763
	b. No	5918

NATIONAL SURVEY

(*Continued from page 28*)

Question 7. Two things stand out in the reply to this question: (1) the emphasis on product development and (2) the general economic aspects of chemical manufacturing, etc.

Question 8 and 9. Probably the first reply (a) to both of these questions should have been anticipated. More returns for the same money seems to be the philosophy. More surprising is the fact that about 40 to 50% of those answering were willing to pay more.

Question 10 to 13. The replies to these local section questions indicate that much improvement is necessary in this field. Apparently the sections are not well enough located for some people. Further study of these replies is in order.

Question 14. The answer to this question puts a significant viewpoint on a much-discussed phase of the undergraduate curriculum. Apparently a good many of the engineers are just as happy without having read about the exploits of Caesar, Virgil, and Theodora.

Question 17 to 20. These can be considered more intelligently when correlations and graphs become available.

Questions 22 to 25. These present a definite opinion on the subject of Registration of Professional Engineers.

Questions 26 to 28. The numbers are self-explanatory in themselves but further correlations will bring out more interesting information. At least half of the members (three fourths of those replying) are employed by private firms or corporations. Also more than 6,000 respondents are employed by firms who employ more than 100 professional or technical people.

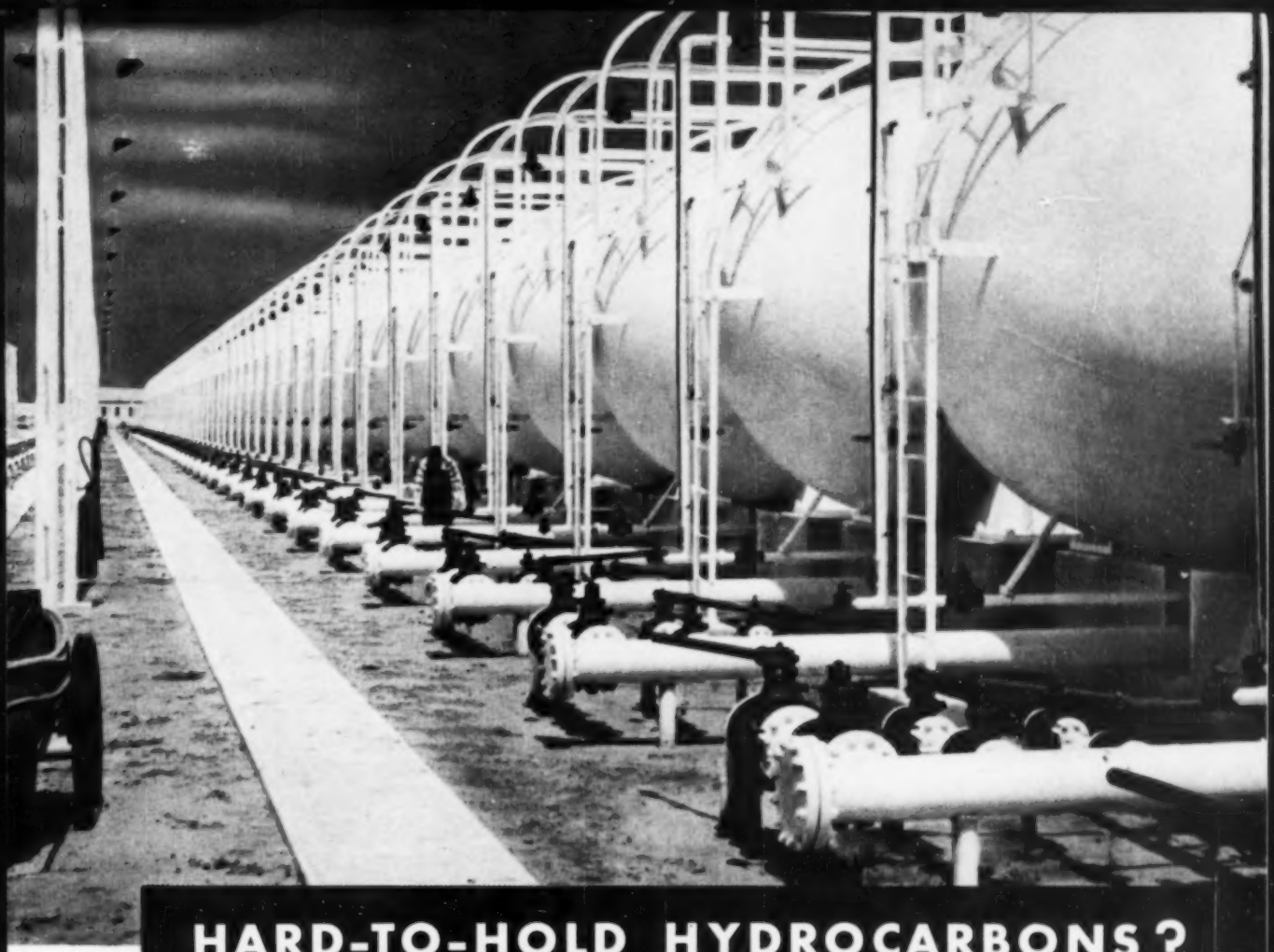
This preliminary report is presented since the large return to the questionnaires must indicate considerable interest on the part of the membership.

NEW NICKEL PLATING PROCESS ANNOUNCED

A new process for nickel plating which requires no electrolytic equipment was announced last month by William J. Stebler, executive vice-president of General American Transportation Corp. According to Mr. Stebler, the new process, which has been tradenamed Kanigen, greatly stretches the available nickel supply in the world, and may "well prove to be one of the most far-reaching industrial developments since World War II."

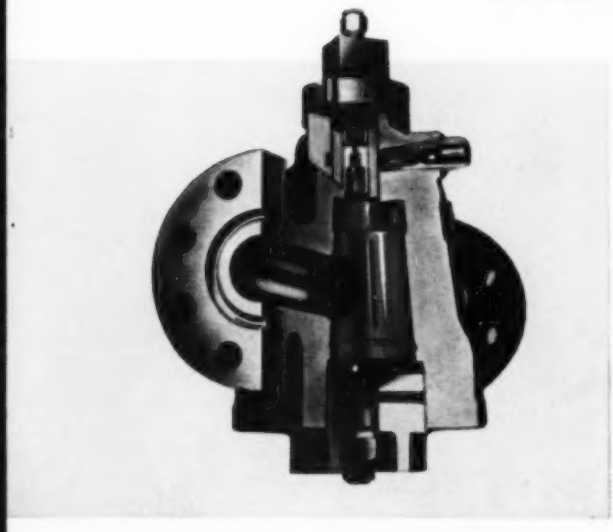
The process, which utilizes a complex nickel chloride sodium hypophosphate solution, is, according to company officials, essentially an improvement on a method developed at the Bureau of Stan-

(*Continued on page 59*)



HARD-TO-HOLD HYDROCARBONS?
Nordstrom *LUBRICANT SEALS* Them

In this case, it's one of the world's largest butane and propane tank batteries that Nordstrom valves are controlling. But it might be any one of hundreds of volatile hard-to-hold hydrocarbons.

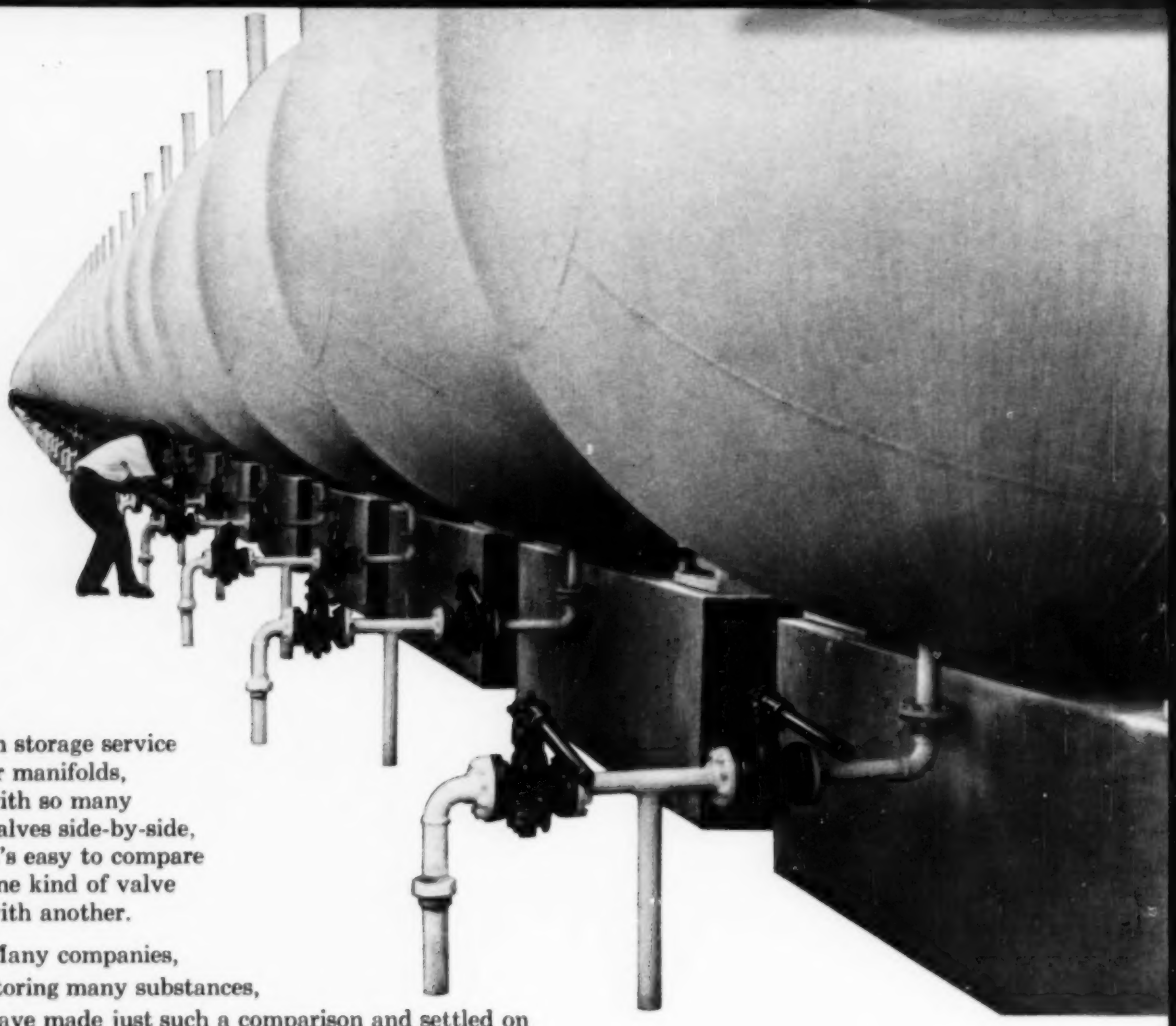


Nordstrom valves don't depend on metal-to-metal contact to check these light, tricky gases and fluids. Nordstrom valves have a seal of plastic lubricant around all seating surfaces—double protection against leaks of inflammable liquids or vapors.

Be sure—really sure. Use Nordstrom valves and genuine Rockwell lubricants. That's the *right* way—that's the *tight* way.
Rockwell Manufacturing Company, Pittsburgh 8, Pa.

ROCKWELL Built
Nordstrom Valves
Lubricant-Sealed for Positive Shut-Off

Another ROCKWELL Product



In storage service
or manifolds,
with so many
valves side-by-side,
it's easy to compare
one kind of valve
with another.

Many companies,
storing many substances,
have made just such a comparison and settled on

NORDSTROM VALVES

Since Nordstrom valves are doubly sealed with an internal film of plastic lubricant, they are doubly protected against the little leaks that can become big dangers. Nordstrom valves operate quickly, too, for it takes only a quarter turn of the plug to change from fully open to fully closed.

AND ROCKWELL LUBRICANT

. . . the same lubricant that adds to valve tightness, acts as a jack to keep the plug ready to turn. Just as they cut costs in nearly every service to which they've been applied, Nordstrom valves and genuine Rockwell lubricants

CUT STORAGE COSTS

Remember, the lowest cost valve is not necessarily the cheapest—
it is the valve which does its job best for the longest time.
Rockwell Manufacturing Company, Pittsburgh 8, Pa.

Nordstrom Valves Another Quality **ROCKWELL** Product

NICKEL PLATING

(Continued from page 56)

dards some years ago by Dr. Brenner. Deposited from the solution at temperatures of about 100° C., the new process successfully coats most metals and a number of organic products such as Bakelite, plastic, and glass. It is not suitable for lead, cadmium, tin or zinc, however, officials stated.

One of the features of the new process is the uniformity of plating which penetrates crevices, threads, and other hard-to-get-at-spots. The cost of the plating was given during the conference as varying from 50 cents to $1.00 per millimeter of thickness per square foot of plating area. The results are about equivalent to dense nickel plating and the speed of plating is about the same, also.

The process, it is claimed, will plate any article uniformly regardless of size or shape, and has proved satisfactory for the production line plating of steel, copper, brass, bronze, stainless steel, and aluminum.

During the conference officials stressed the fact that owing to its greater efficiency in giving equivalent protection with one-third to one-half the nickel required by other processes, and because of the nonporosity of the plate, important savings in critical nickel could be realized by the nation.

General American originally developed the process for the interior coating of tank cars carrying corrosive chemicals in an attempt to eliminate the pickup of iron by the chemicals from the tank-car metal. The fact that the new nickel plating process has 100% throwing power makes it practical to plate pieces of any shape or size.

Composition of Plate

The Kanigen plate is a nickel-nickel phosphide composition with about 5 to 8% phosphorus and a Vickers hardness of 550-650. Adhesion, according to the company, is excellent; the plate is of uniform thickness, having no more than 5% average variations between maximum and minimum. It was stated during the conference that thickness may at present be controlled to within one ten thousandth of an inch.

The company is at present building two plants, one at E. Chicago, Ill., and one at Los Angeles, Calif. Present plans are to plate equipment sent in by customers, and eventually General American intends to license the process to other platers.

More information can be obtained on the process, technical data being available from the General American Transportation Corp., 135 S. LaSalle St., Chicago 90, Ill.

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Weaves that STOP the Solids!

Enlargements 4X

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Study the shape of the solids in your solution being filtered. That's just as important as the size, if you want clarity of filtrate. Then write us fully about the solids and we'll be glad to recommend the weave of the cloth that will "stop" them.

Many malleable metals are still available so, if necessary, we can probably supply you with a material that will also withstand highly corrosive conditions. When writing, also give solution characteristics.

All Newark Filter Cloths are woven in our own plant, on our own looms, by our own skilled weavers.

Our entire line of Filter Cloths, Wire Mesh and Space Cloth, Sieves, "End-Shāk" Testing Units and other Newark Products are described fully in our new Catalog D. Send for a copy.

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Simplify selection; standardize on fewer types, models, sizes; minimize maintenance problems.

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- *Volume:* ½ to 10 g.p.m. maximum at 1750 RPM (water).
- *Pressures:* to 70 psi.
- *Suction Lift:* Highest over widest temperature and viscosity range.
- *Corrosion Resistance:* Lowest corrosion rate due to internal flow pattern. Handles all chemicals that stainless steel No. 316 will handle.
- *Pump Operating Characteristics:* Linear delivery. No air entrainment. Non-foaming. Unequalled for safety in handling hazardous liquids such as nitric acid and hydrogen peroxide. Self-priming on non-volatile liquids.
- *Drive:* Applicable to direct motor drive at 1750 RPM, as well as to all other standard driving methods.

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LOCAL SECTION

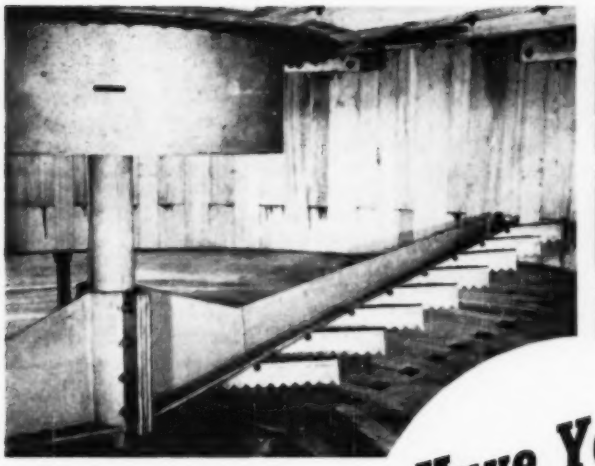
This editor wishes to thank *W. M. Otto* of the Akron Section for his account of the February and March meetings. At the former meeting J. Y. Oldshue, Mixing Equipment Co., talked on "Mixing: Art or Science?" His talk was illustrated with slides and motion pictures showing gas-liquid contacting through the eyes of the Eastman high-speed camera. About 100 members and guests attended and participated in an active discussion period. At the March 12 meeting, Byron Ellis, Midwest representative of the National Research Corp., talked on "Vacuum Engineering and Its General Applications." Some of the more novel applications of high vacuum in industry, such as concentration of frozen fruit juices, metallizing of plastics and papers, and atomic energy applications were covered. A coffee talk was presented by H. N. Haberstroh, Jr., sales engineer, Johns-Manville Products Corp., Celite division.

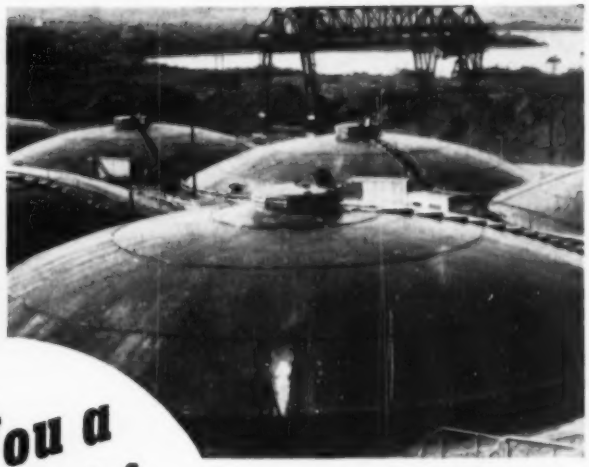
Officers of the New Orleans Section for 1953 are as follows: Henri J. Molaison, chairman, Francis M. Taylor, vice-chairman, and Hugh W. Black, secretary-treasurer. Other executive committeemen: Raymond V. Bailey, John R. Tusson, Kenneth M. Docossas, and Leon Godchaux. This information along with a report on the Feb. 3 meeting came from *Alton S. Hall*, chairman, publicity committee. At that meeting J. W. Bertetti, general manager of manufacturing, Pan-Am Southern Corp. stated that fluid hydroforming is a cheaper, better means of upgrading low octane gasoline.

The seventh meeting of the Philadelphia-Wilmington Section of A.I.Ch.E. featured a talk titled "Solvent Extraction" by Joseph C. Elgin, professor of chemical engineering, Princeton University. About 110 members and guests were present. At the previous meeting held Feb. 10, at the Rodney Hotel, Wilmington, Del., Richard Gorman of Carbide and Carbon Chemicals Co., talked on coal hydrogenation. Approximately 140 members and guests heard the subject covered from the standpoint of process description and the possible economic significance to the United States. Another interesting piece of news concerning this Section is the announcement of the one-day meeting. See page 31.

At the last meeting of the El Dorado Section held at the Lion Oil Chemical plant cafeteria, forty-three members and guests were present. In connection with Engineers' Week, R. J. Rhinehart, Arkansas Power and Light Co., spoke on "Registration for Engineers." Referring to the pride of the profession, Rhinehart outlined the history of engineering and the engineers' contributions

(*Continued on page 62*)





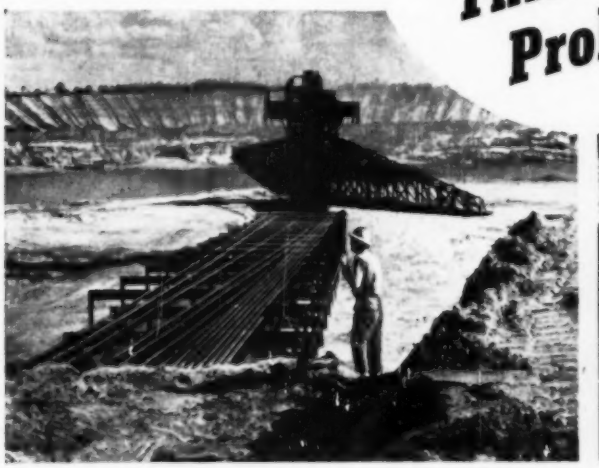
Have You a SPECIAL Thickening Problem?

Closeup of a special Dorr Tray Thickener with rubber covered mechanism and serrated rake blades. Lead covered steel, wood and stainless steel units have also been fabricated.

A special 300 ft. dia. Dorr Thickener equipped with picket arms and a flocculating feedwell installed in a 750 ft. dia. earthen basin clarifies 15,000 gpm of phosphate rock tailings.

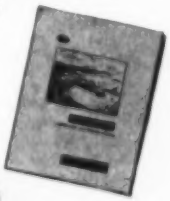
Dorr Thickeners are covered with concrete domes to minimize ammonia loss in a nickel leaching plant. Covered Dorr Thickeners are also used in the pigments industry where size precludes indoor installation.

One of the largest water recovery plants in the east uses three 250 ft. dia. Dorr Torq* Thickeners installed in a single earthen basin. Almost 5 acres of surface area is provided with a capacity of 14½ million gallons per day.



Many thickening problems in the process industries can't be solved by standard methods. It's here that Dorr's ability to provide a special unit, tailor-made for the special job, pays dividends. Here are four recent examples. If your problem requires a fresh approach, why not check Dorr . . . the oldest manufacturer of sedimentation equipment . . . *with the newest ideas*. Write for your copy of Bulletin No. 3001 "Dorr Thickeners for chemical, metallurgical and industrial processing." The Dorr Company, Engineers, Stamford, Connecticut.

*Reg. U. S. Pat. Off.



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AIR LIFT DRIER offers a new and revolutionary method capable of great flexibility to cover load and material variations. Wider adaptability is possible when unit is designed for a specific product.

An increased yield of product is attained with the air suspension unit —actual tests with identical material showing 8% to 10% recovery in excess of that from direct fire, high temperature methods.

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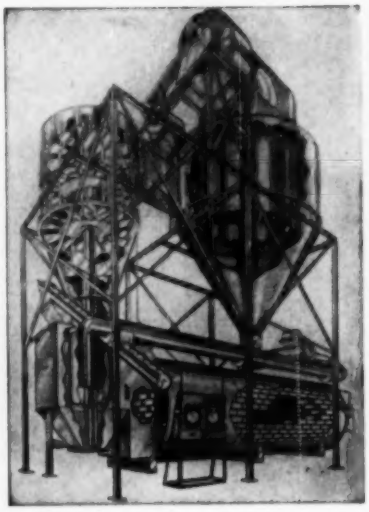

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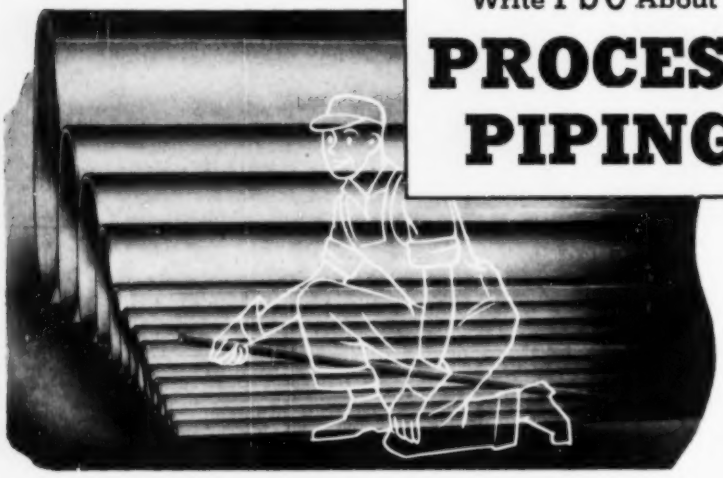

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LOCAL SECTION NEWS

(*Continued from page 60*)

to human betterment. *Edward A. White*, publicity chairman of the Section, reports that the engineer's duties as a citizen were emphasized and a canon of ethics was discussed. The speaker urged that all engineers present seek registration as a means of advancing their profession and themselves.

The Tennessee Valley Section met jointly with the North Alabama Section of the A.C.S. on Feb. 23 at the Decatur High School, Decatur, at which Francis J. Curtis, President of A.I.Ch.E. (1949) and vice-president and director of Monsanto Chemical Co., gave an address titled "Human Engineering in Science," and discussed management development. *Nathan Gilbert*, chairman of this Section, reports on the enthusiasm of the members to make this a successful and active year.

At The Ohio State University Faculty Club, the Central Ohio Section gathered for a dinner meeting on March 10 to hear John Calbeck, director of research, pigment division, American Zinc Oxide Co., discuss the manufacture and use of industrial zinc oxide. *G. F. Sachsel*, publicity chairman of the Section, reports that the publicity committee of the section participated in National Engineers Week with a window display in a downtown location, highlighting the contributions of chemical engineers to the public welfare and standard of living.

"Chemical Development and Engineering Materials" was the title of an address given by H. L. Maxwell, president of the American Society for Testing Materials, before the joint meeting on March 27, of the South Texas Section of A.I.Ch.E. and the southwestern district of American Society for Testing Materials, now being organized. One feature of the meeting was a visit to the modern manufacturing facilities of the Cook Paint and Varnish Co. This was followed by a social hour and dinner in the Orchid Room of the Alabama Catering Service, Houston. *N. H. McKay*, who reports regularly to us, states that there was plenty of barbecue or fish. The next meeting of the South Texas Section is planned for April 24 at Oberholtzer Hall on the campus of the University of Houston. Hugh Bernard, vice-president of the Second National Bank of Houston, speaking under the auspices of the Better Business Bureau, will present a talk titled "Frauds and Fakers."

The triumvirate of *West, Morrissey and Black* has sent in a report on the sixth monthly meeting of the Pittsburgh Section which was held in the Mellon Institute Auditorium on March 11,

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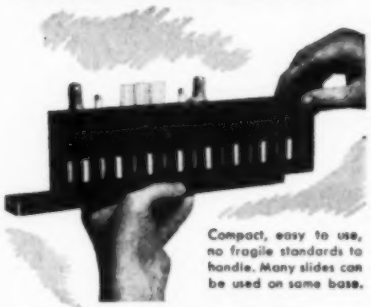

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1953. This was set aside as Annual Student Night. Students from West Virginia University, Grove City College, Carnegie Institute of Technology and the University of Pittsburgh were welcomed after which H. L. Barnebey, a guest speaker, outlined the steps involved in starting a new chemical enterprise in "How Chemical Plants are Born." In the building of a plant to make a new product, he referred to the various stages a process goes through. For instance, he said there is the laboratory research or idea stage; the product evaluation stage in which cost and market analyses are made; the process study stage; the preliminary engineering stage during which a preliminary design and cost estimate are made; and last a pilot plant study culminating in the building of the commercial plant. At the social hour the students had an opportunity to talk individually with members of the panel who are employed by various companies and in different phases of chemical engineering work.

E. A. Lawrence of Colgate-Palmolive-Peet is going to address the New York Section on April 22 on the subject titled "Chemical Engineering from Soap to Salad."

Bernard H. Rosen, publicity chairman, states that Dr. Lawrence will discuss the technology of edible and inedible fats and oils. The meeting will take place at high noon at the Brass Rail on Seventh Avenue, New York.

At the meeting on Feb. 17, Elwood Moffett, assistant to the chairman of the organizing committee of District 50, United Mine Workers of America, was the speaker who gave his own views on certain controversial subjects such as the Taft-Hartley Act.

Truman B. Bishop, chairman, publicity committee, Midland Section, has sent in the names of the officers for 1953. They are: J. W. Corey, chairman; K. E. Coulter, vice-chairman; J. H. Wardwell, secretary-treasurer; E. G. Sprague, R. E. Withrow, Jr., and N. Poffenberger members, executive committee. Mr. Poffenberger is the retiring chairman. At the Feb. 27 meeting, Donald L. Katz, chairman, department of chemical and metallurgical engineering, University of Michigan, addressed eighty members and guests of the Section at the Dow Auditorium. In "Can Chemical Engineering Avoid the Handbook Stage?" he traced the growth of chemical engineering education and discussed the problems that have come with this growth. At the previous meeting, Walter Coopey, consulting engineer, talked to about ninety members and guests on the fundamentals of pump packing. Preceding the talk a film was shown titled "How to Build a Tire" by the Firestone Rubber Co. Note: We were in error in stating in the March issue, page 58, that this Section was "conspicuously silent." The reference was to "No News" of its activities for the January and February, 1953, departments of local section now covered. As a matter of fact the Midland Section sent in many and interesting accounts in 1952 and judging by present indications will likely continue.

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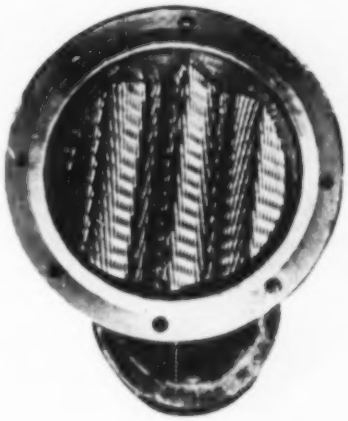

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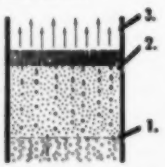

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It is heartening to report that the membership of the Central Pennsylvania Chemical Engineers' Club has increased to fifty engineers in that area since the first annual meeting in December, 1952. At the March 18 meeting, H. Vogt and E. K. Lofberg of the Corning Glass Co. discussed the properties of glass. At the meeting on Feb. 18, Harold Heine of Bucknell University addressed the group on "The Biochemistry of Lockjaw." *Lester Berkowitz* writes that plans are in the making for offering a program of technical courses of interest to the members. The officers of this club whose names have not been listed here are: W. E. Keppler, Merck & Co., Inc., chairman; R. Slonaker, Bucknell University, vice-chairman; L. Berkowitz, Merck, secretary; L. L. Williams, Merck, treasurer; and J. Balog, J. Lago and J. Plonko, Merck, committee chairmen.

Fifty were present at dinner at the Engineers Club, Baltimore, Md., on Feb. 17 and approximately seventy heard Charles M. Cooper, Du Pont Co., give a talk under the title "Tools versus Information." This meeting was a successful one with senior chemical engineering students from the University of Maryland guests at the dinner and meeting. *Calvin Palmer*, secretary-treasurer, Maryland Section, reports that at the March 17 meeting senior chemical engineering students of Johns-Hopkins University were guests under a similar arrangement and heard Sidney D. Kirkpatrick, the principal speaker.

Nelson Morley, reporter of the Ohio Valley Section, tells us that at the February meeting at the Cincinnati Engineering Society headquarters, A. C. Brown reported on the progress of the plans for the Symposium which will be held in Cincinnati. The speaker for the evening was Richard D. Boutros, chief engineer, Mixing Equipment Co., who discussed mechanical design and operation of fluid mixers.

"Fluorination of Tulsa City Water" was the subject of a symposium given before the Tulsa Section on Feb. 18 at the Alvin Hotel. The speakers were (1) Max G. Armstrong, D.D.S., who reviewed the history of fluorination and presented the dental aspects of this subject; (2) Wayne E. White, fluorine research director, Ozark-Mahoning Co., who covered the chemistry of fluorination, and (3) Curtis Moutrey, superintendent of plants, Tulsa City Water Department, who talked about fluorination of water from the Water Department viewpoint. *Ray J. Stanclift, Jr.*, reporting the event, added that the speakers sat as a panel to answer questions.

The problems and advantages of outdoor chemical plants was the subject of the talk presented by W. H. Williams of the Dow Chemical Co. at the February meeting of the Chicago Section. *A. M. Holzberg*, technical representative, reports that Mr. Williams drew upon Dow's experience to bring to his hearers the main points to be considered in outdoor plant construction.

The seventh meeting of the Northeastern New York Section included a tour of the General Aniline Works in Troy, N. Y. The group of approximately forty-five was addressed by Joseph W. Conlon, production manager, who described the operations of the General Aniline Works and gave a brief history of the company. *Harry H. Steinhauser, Jr.*, informs us that men from General Aniline acted as guides.

At the February meeting of the Northern California Section, held at the Engineers' Club in San Francisco, an unusually large attendance gathered to hear a talk by Mott Souders, Jr. The speaker, an associate director of the Shell Development Co., discussed the comparative positions of chemical companies and petroleum companies as investments. From an analysis of the past records of a number of representative companies of each group, *D. F. Rynning* reports, the speaker was able to show the basic differences in the financial character of the two industries. He then pointed out the significance of these characteristics to those investing in such industries either directly or through the stock market.

The February 24, 1953, meeting of the Charleston Section was held at the Charleston Recreation Center with 142 members and guests present to hear L. V. Sherwood, manager of the Agricultural Chemicals Section of Monsanto organic chemicals division, development department, talk on "Soil Conditioners." He reviewed the historical background which has led to the development of soil conditioners and emphasized that soil conditioners do not automatically create soil structure but rather merely bond the soil in the physical state in which it exists at the time the conditoner is added. Dr. Sherwood concluded his talk with a 20-min. motion picture in color showing the application of soil conditioners. The film demonstrated the ability of soil conditioners to increase ability of soils to absorb and hold moisture. *A. G. Draeger*, secretary of the Section, is responsible for our knowing about this instructive talk.

At a recent meeting of the Enlisted Specialists Chemical Engineering Club, Army Chemical Center, Md., L. F. Audrieth, professor of chemistry, University of Illinois, gave a lecture on hydrazine, a speciality fuel which could be considered for rocket propulsion. Dr. Audrieth who is visiting the Army Chemical Center as a consultant, is responsible for much research on hydrazine dehydration.

—H.R.G.

PEOPLE

Waldo B. Burnett has been appointed technical director of United Carbon Co., Inc., Charleston, W. Va. Dr. Burnett recently resigned as director of the University of Wichita Foundation for Industrial Research, which has done considerable research work for United Carbon during the past few years. Before establishing headquarters in Charleston, he will spend several months studying production problems in the various plants. United Carbon is a producer of carbon black for the rubber, ink and other industries.

The appointment of **Edward H. Sundbeck** to duties in the research and development department of The Chemstrand Corp., Decatur, Ala., was recently announced. He is a group leader of the general process section, and has been engaged on special assignments with Chemstrand at the pilot plant at Marcus Hook, Pa., and at Wilmington, Del. He was a research chemical engineer with Du Pont Co. for ten years and with the Dorr Co., Westport, Conn., for eight years. Mr. Sundbeck received a B.S. degree in chemical engineering from New York University.

The appointment of **Frederic A. Soderberg** as vice-president of F. C. Huyck & Sons in charge of sales for the paper-maker felts and mechanical fabrics division has recently been announced. Prior to his new position, he served as manager of the Industrial division of the General Dyestuff Corp. His professional career began at the Rumford, Me., plant of the International Paper Co. by working as a broke handler, beater engineer, and development engineer. He is a graduate of the University of Maine and received his degree of professional chemical engineer from the same institution.

John Procopi has recently joined the Milton Roy organization as manager, market development department. He was formerly with Brown Instruments Division of Minneapolis - Honeywell Regulator Co. Mr. Procopi is a graduate of Columbia University.

Frank Lerman is now serving as a research chemical engineer with the Illinois Institute of Technology, Chicago, Ill. He is the author of the Liquid-Solid Extraction section in Encyclopedia of Chemical Engineering Technology.

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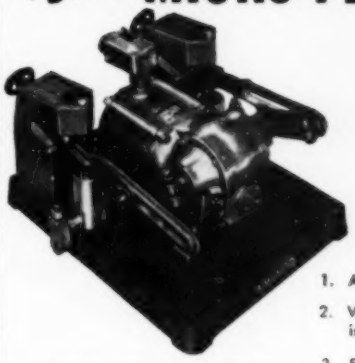

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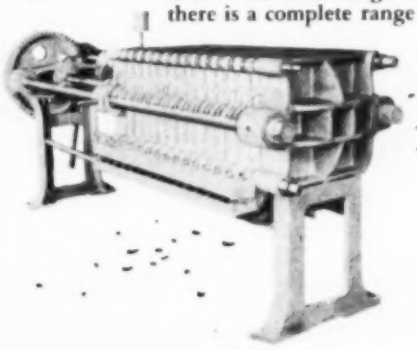

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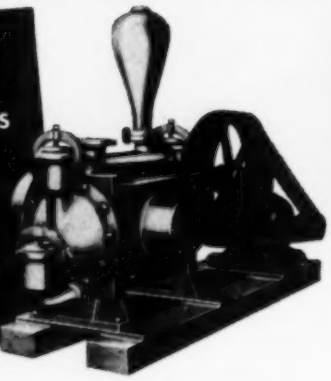

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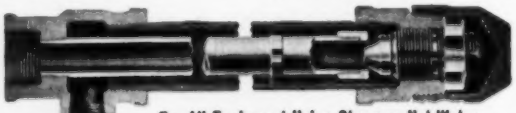

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Paul N. Cheremisinoff resigned from the research department of Swan-Finch Oil Corp., Hackensack, N. J. on Feb. 20 to join the Crown Chemical Co.'s division of Joseph Turner & Co., in Ridgefield, N. J., as a technical director. In this capacity he will be in charge of all manufacturing and development work in the organization with the exception of the dyestuff division. A former employer of Mr. Cheremisinoff was M. W. Parsons-Plymouth, Inc., Brooklyn, N. Y. He received his Ch.E. degree from Pratt Institute.

John H. McCormick, technical representative, is now in charge of the new district sales office, textile fibers department of Carbide and Carbon Chemicals Co., Charlotte, N. C. Mr. McCormick, who spent three years as an officer in the U. S. Air Force during World War II, was graduated from the University of West Virginia with a B.S. degree in chemical engineering in 1947. He received his M.S. degree in 1948 and joined Carbide and Carbon Chemicals immediately, where he has since been associated with the development of Dynel.

Robert H. Stevens, retired technical director, National Container Corp., Jacksonville, Fla., has joined the staff of the Herty Foundation Laboratory, Savannah, Ga., as research associate. Spending thirty-five years in the pulp and paper industry, Mr. Stevens has been associated with many companies including the Halifax Paper Corp., Roanoke Rapids, N. C.; Albemarle Paper Manufacturing Co., Richmond, Va.; American Dyewood Co., Mobile, Ala.; Bogalusa Paper Co. (now Gaylord Container Corp.) and Sorg Paper Co.

Earl D. Oliver and **Edwin T. Williams** have recently joined the staff of Shell Development Co., Emeryville, Calif. Oliver received his B.S. and M.S. degrees in chemical engineering at the University of Washington. Before joining the staff of Shell, Williams was an instructor in chemical engineering at Penn State.

James C. Barnett, a research group leader at Monsanto Chemical Co., Monsanto, Tenn., will head a research group on process and product development at Dayton, Ohio. Barnett received his B.S. degree from Alabama Polytechnic Institute and joined the phosphate division, research department at Anniston, Ala., shortly after receiving his degree.

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J. M. AVERY JOINS ETHYL

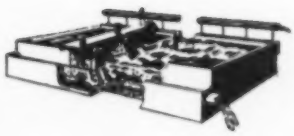
Julian M. Avery, who has been a consultant to Ethyl Corp. for the past two years, has joined the Ethyl staff as a technical adviser. He will work primarily with the company's planning group on product development and research programs, and will be in charge of technical contacts in foreign countries.

After receiving his degree in electrochemical engineering from Massachusetts Institute of Technology in 1918, Mr. Avery served for a year with the Chemical Warfare Service. He joined Union Carbide and Carbon Corp. in 1919, spending a large portion of the next seventeen years in Europe. For the next five years he was associated with A. D. Little, Inc., as an engineering consultant and New York representative. In 1941 he joined Diamond Alkali Co., and served as vice-president and director of research and development until 1946. He then returned to New York to establish a private consulting practice and at that time he became a director of Chemical Fund, Inc.

Edwin M. Haun has been named a project supervisor in Monsanto Chemical Co.'s recently organized overseas division. He will assist in the creation and operation of a project system for handling development projects of that division in cooperation with the other divisions and the general development and patent department. After graduating from the University of Illinois, he joined Monsanto as a research chemist at the phosphate division's Anniston, Ala., plant. In 1943 he became production supervisor there and in 1945 he joined the company's general development department at St. Louis. He has been a member of the phosphate division's development department since 1950.

Donald J. Miller was recently appointed manager of Monsanto Chemical Co.'s new plant at Avon, Calif. **Frank S. Bonham** will succeed Miller as manager of the company's Long Beach plant. Mr. Miller was graduated from Washington University in 1941 with a chemical engineering degree and joined Monsanto in that year at its Springfield, Mass., plastics division plant. During World War II he served with the United States Navy and after the war returned to Springfield as a laboratory supervisor.

J. R. Phillips is now assistant general operation manager at Mississippi Chemical Corp., Yazoo City, Miss. Prior to that he was employed by the Girdler Corp. in the gas processes division as chief operating engineer.



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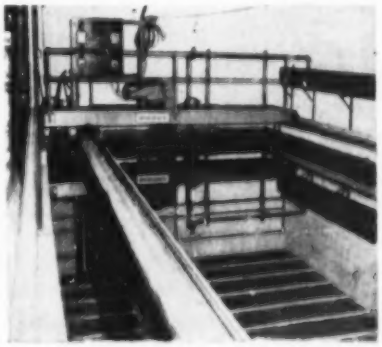

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C-11

The post of director of research in the plant food division of Swift & Co., Chicago, Ill., has been given to **M. D. Sanders,** a veteran of twenty-seven years with Swift excepting three years in service during World War II. Joining Swift in 1925 as a chemist, Mr. Sanders became assistant to the late Doctor Siems in the Chicago plant food laboratory two years later, then manager of the Harvey, La., laboratory in 1932. Sanders returned to Chicago in 1935 as head of the chemical engineering division research laboratory and remained until he entered the Air Force in 1942. Since 1945 he has served in his prewar post with the Chicago research laboratory.

W. E. Kennel, formerly group leader, has been made section leader in the chemical products division at Standard Oil Co.'s Whiting, Ind., research laboratories. **V. J. O'Brien, Jr.,** was appointed group leader in the same division. Dr. Kennel joined Standard in 1948 as a chemical engineer, and was advanced to group leader in 1952. He is a graduate of the University of Illinois, and received a master's and doctor's degree from Massachusetts Institute of Technology. Dr. O'Brien, associated with the company since 1950 as a chemical engineer, is a graduate of the University of Illinois, and holds a master's and doctor's degree from Pennsylvania State College.

Formerly of the U. S. Bureau of Mines, Albany, Ore., **I. J. Groce** has accepted a position as chemical engineer with Metal Hydrides, Inc., Beverly, Mass. In this capacity he will be concerned with the development of new processes and products. Mr. Groce is a graduate of the University of Washington, and has been intimately connected with the production of zirconium.

John H. Wishnick, manager of the Chicago plant of Witco Chemical Co., New York, has been placed in charge of chemical manufacturing at the Chicago and Brooklyn plants. He went to Witco as a petroleum engineer for the Continental Carbon Co. after graduating from the University of Oklahoma in 1948.

The transfer of **Robert G. Powell** to Monsanto's new sulfuric acid and phenol plant at Avon, Calif., and the promotion of **Charles T. Murray** as supervisor of the vinyl chloride production at Texas City were recently announced. Mr. Powell has been with Monsanto in Texas City for the past seven years, serving as area supervisor of the alkylation and more recently, as supervisor of vinyl chloride production. Prior to going to Monsanto in 1946, Mr. Powell served with the U. S. Army Chemical Warfare Service.

Mr. Murray joined Monsanto at Springfield, Mass., in 1947 in process investigation, and in 1951 was transferred to Texas City to become operating supervisor in the production department. He was assistant to Mr. Powell in the vinyl chloride production department. Mr. Murray received his B.S. degree from Georgia Tech, and studied chemical engineering in the graduate school at the Massachusetts Institute of Technology.

John T. Stephan is now associate director of research for Monsanto Chemical Co.'s Western division, Seattle, Wash., effective April 1. He received his B.S. and M.S. degrees in chemistry from Washington University. In 1935 he was employed by the I. F. Laucks Co., later acquired by Monsanto.

Charles Harford of Arthur D. Little, Inc. is now traveling in Egypt to complete a housing project for the Government of Egypt. The program is part of the United States Point Four Plan to help underdeveloped countries by giving them scientific and technological aid.

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Bernet S. Swanson, assistant professor of chemical engineering at Illinois Institute of Technology, has been appointed executive officer of the department. Dr. Swanson replaces Dr. J. Henry Rushton as head of the department. Dr. Rushton requested that he be relieved of his administrative duties so that he might devote more time to research, writing and consultation work. He will continue as professor of chemical engineering. Educated at Illinois, Dr. Swanson received his B.S. in 1942, his M.S. in 1944, and his Ph.D. in 1950. He taught chemical engineering in Kansas State College in 1947-48 after teaching at Illinois Tech for three years. He returned to Illinois Tech in 1948 as assistant professor of chemical engineering.

Robert E. Lyon has joined the staff of the Whiting Research Laboratories of Standard Oil Co. (Ind.). Dr. Lyon obtained his bachelor's and master's degrees at the Michigan College of Mining and Technology and obtained his Ph.D. degree in chemical engineering at the University of Michigan.

The assignment of **L. William Sessions** to the branch sales office of Monsanto Chemical Co.'s organic chemicals division, St. Louis, Mo., has been announced. He joined the development group of the company's John F. Queeny plant in 1946 and was transferred to the organic chemicals division's sales department in 1948. He received his B.S. degree in chemical engineering from the University of Michigan.

John D. Fennebresque, vice-president and assistant to the president of Celanese Corporation of America, has been elected to the board of directors of the company. He joined the company in 1944, and was general manager of the chemical division for several years. He was elected vice-president in 1951.

R. V. Becknell, formerly project manager, has been appointed manager of the project engineering department of the M. W. Kellogg Co., a subsidiary of Pullman, Inc. Mr. Becknell will serve as administrative head of the department and in addition will be technically responsible for the project engineering on all company contract work in North, South and Central America. He received his B.S. degree in chemical engineering from Oklahoma A&M College.

(Necrology on page 72)

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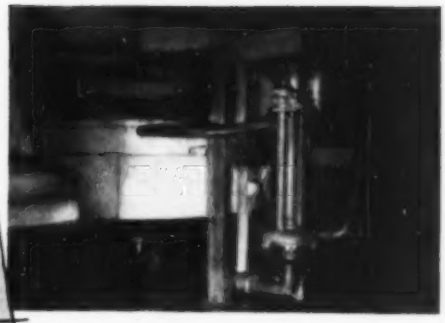

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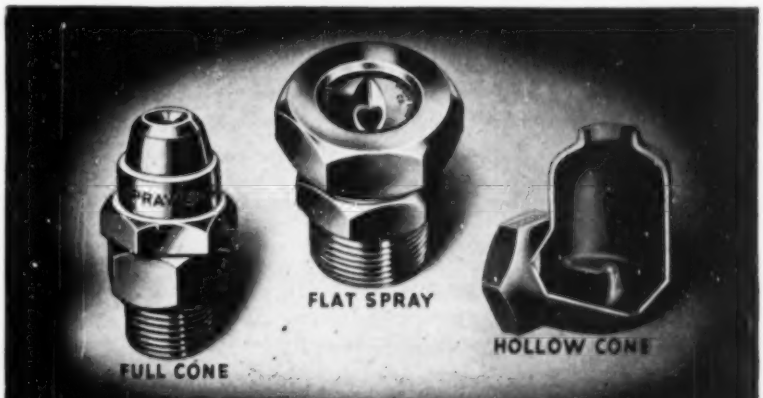

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Necrology

J. R. WITHROW

James R. Withrow died on March 20, 1953, at Cleveland, Ohio, following a short illness.

Dr. Withrow received his B.S. degree in 1899 from the University of Pennsylvania. He then entered the employ of the Barrett Co. where he worked for about three years, returning to the University of Pennsylvania from which he received his Ph.D. in 1905. Subsequently he entered the teaching field at the University of Illinois and in 1906 went to Ohio State University where he remained until his retirement about two years ago.

Dr. Withrow joined the Institute in 1911 and had been active in its affairs serving three terms on Council, 1913-1915, 1917-1919, and 1934-1936, and on the Chemical Engineering Education and Accrediting Committee.

Dr. Withrow was well known through his consulting practice.

E. C. BARELL

Emil C. Barell, recently retired international president of F. Hoffmann-La Roche and Co., Ltd., died in Basle, Switzerland, on March 17.

Doctor Barell was associated with F. Hoffmann-La Roche and Co., Ltd., for a period of fifty-seven years and, for more than half a century, was the chief executive officer of the firm. In addition to his degree as Ph.D. in chemistry, which he received from the University of Berne, Doctor Barell received four honorary degrees from leading universities in Switzerland.

He was best known in this country for his pioneer work in developing facilities for large-scale production of vitamins.

Doctor Barell was 79 years old.

D. G. ANDERSON

David G. Anderson, Jr., chemical engineer with the Atlas Powder Co., Wilmington, Del., since 1946, died March 7, 1953. After obtaining his doctorate at Columbia University, Dr. Anderson served as a project leader at the University of Delaware on secret war research, which was under the Office of Scientific Research and Development. Before becoming associated with the Atlas Powder, he was with Westinghouse Electric Co., Pittsburgh, Pa. He also served as an instructor of chemical engineering, College of the City of New York.

M. T. DUNBAR

Mahlon Thompson Dunbar, a B.S. from the University of Maine in 1951, died recently. He was 23 years old.

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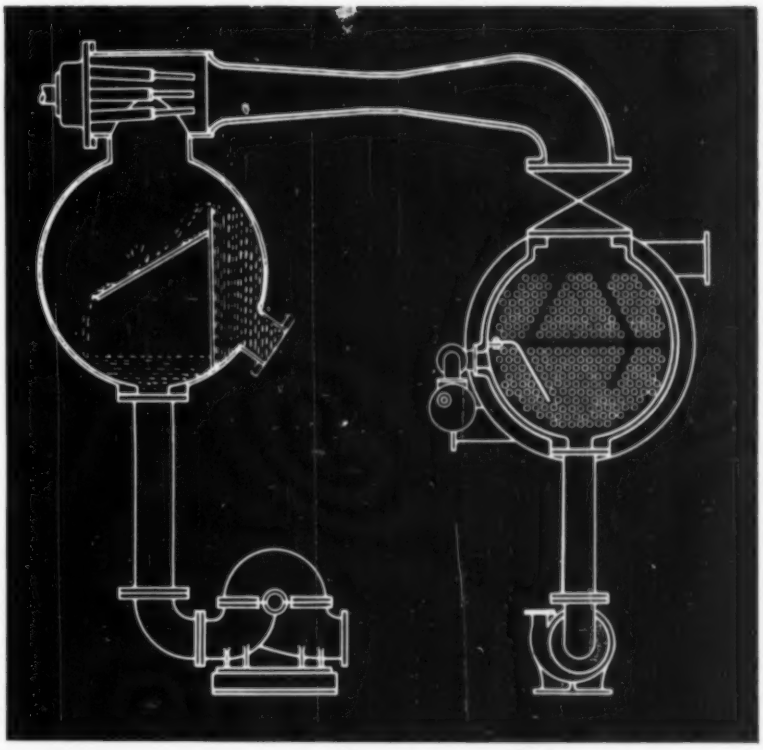

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THE PRESIDENT SAYS

"Ever notice how often they find reasons why an idea won't work?"

Seems to me most people can imagine failure more easily than they can imagine success. Ever notice how often they find reasons why an idea *won't* work? And how afraid they are to try new things? I recently suggested to members of one of our sections that they try a one-day meeting to attract chemical engineers from all around their area. The first question asked was, "How much help can we get from the national organization?" This certainly betrayed fear of failure and these men weren't being abnormal or unusual. This seems to be a typical reaction.

The very same men do tremendous things and carry enormous responsibilities in their own familiar fields of action. I must conclude that they do not readily imagine being successful in a new type of enterprise. Yet, this is one of the real keys to success in any field. Life is intolerable if a man imagines himself to be a failure. A technical project is foredoomed if it is imagined that it cannot succeed.

I wonder if apparent inability to be creative is really due to inability to think up ideas or inability to imagine ideas being successful. There must be literally hundreds of ways in which each of our fifty sections can function so as to interest and edify its members and, in addition, perform public service in accordance with the highest ideals of the professional group. Yet, most sections seem to stick pretty close to a stereotyped program featuring a conventional dinner followed by a conventional speech of some kind. Surely, more variety would be welcome and there ought to be a public- or community-service aspect included in any professional group's program. If ability to imagine success in undertaking new and untried types of activity will help, then a change in attitude and habits of thought may be all that is required. This comes free to all.

* * * * * *

Nowadays up-to-date business organizations try to keep lines of communications open in both directions inside the company. Exactly the same sort of thing pertains to a professional society such as A.I.Ch.E.

Our members are more than ordinarily interested, as witness the fact that the returned questionnaires in our national survey far outnumber the usual response to such questionnaires. This survey was organized for the express purpose of opening up a line of communication and finding out what members are thinking about certain subjects. Answers are being tabulated, and preliminary results should be available soon.

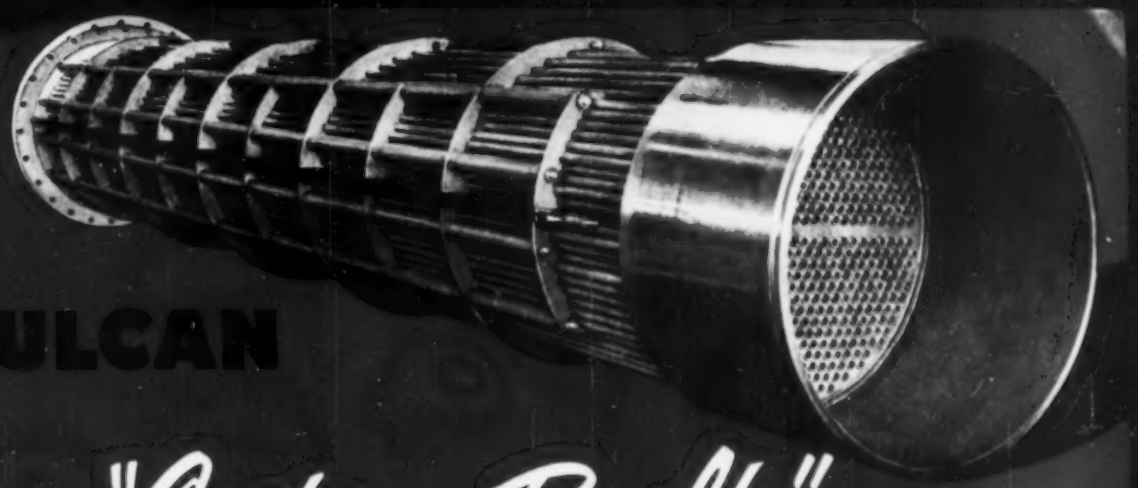
* * * * * *

I am getting some surprises as I go about the business of being President of your Institute. It is taking more time than I anticipated primarily because I am getting more mail than I expected. Quite a large part of my evenings and week ends is devoted to correspondence. I do not begrudge this time since it means that communications are open to some extent at least. Most of the letters I receive from members are constructive and a good bit of the content deals with matters in which the writer is in general agreement with me or with Council or Institute tradition. There is an encouraging amount of well-thought-out material which represents sort of "loyal opposition" and, of course, there is a little bit of stuff which is written in the heat of anger. It is always pleasant to have your views confirmed by thoughtful people. Sometimes you learn more, though, from people who do not agree with you.

I do like to receive constructive proposals for worthwhile Institute activities, even though they may seem contrary to tradition, for these are the raw materials of progress.

We have some important Institute problems to solve, and no doubt the response to our questionnaire will pose some more. It is pleasant for me to be able to tell you that the 1953 Council is a real working body and may be expected to find practical solutions for a good many of our most pressing problems. As time goes on I hope to tell you more about some of these problems and what we are doing about solving them. That is the purpose of this column.

W. J. Nichols



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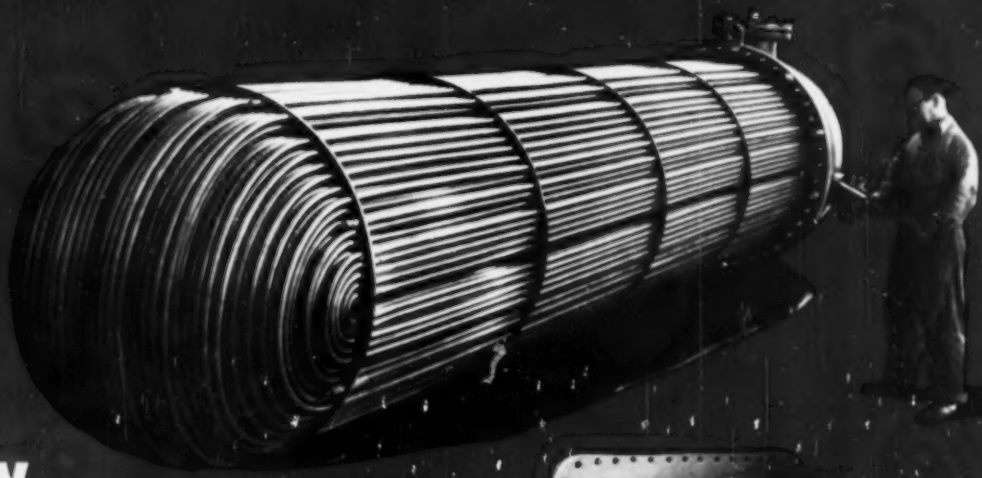

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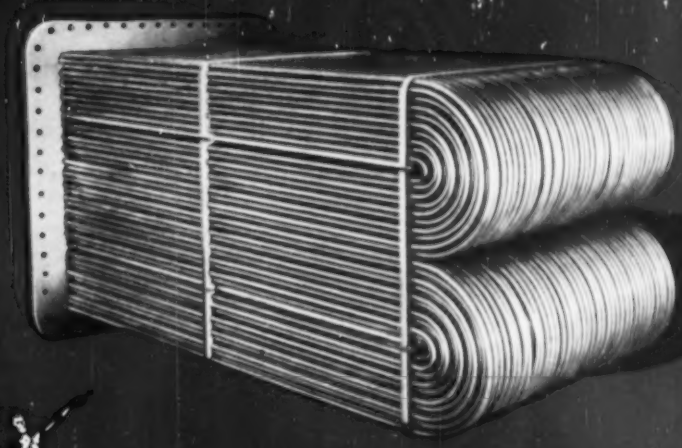

When heat exchangers are designed and built to meet specific process conditions ranging from liquid air to Dowtherm, high vacuum to high pressure. Quality construction emphasizes long life and meets ASME or TEMA requirements.

Vulcan can study the particular problem and supply the design or build the equipment from design furnished by the customer. Assistance is given the customer in the economic selection of shell and tube types to be fabricated either fixed bundle or removable bundle with floating or outside packed head.

Materials of construction include stainless steel, carbon steel, nickel, copper, Everdur, phosphor-bronze, aluminum, Monel, Hastelloy, Ampco, and Karbate.

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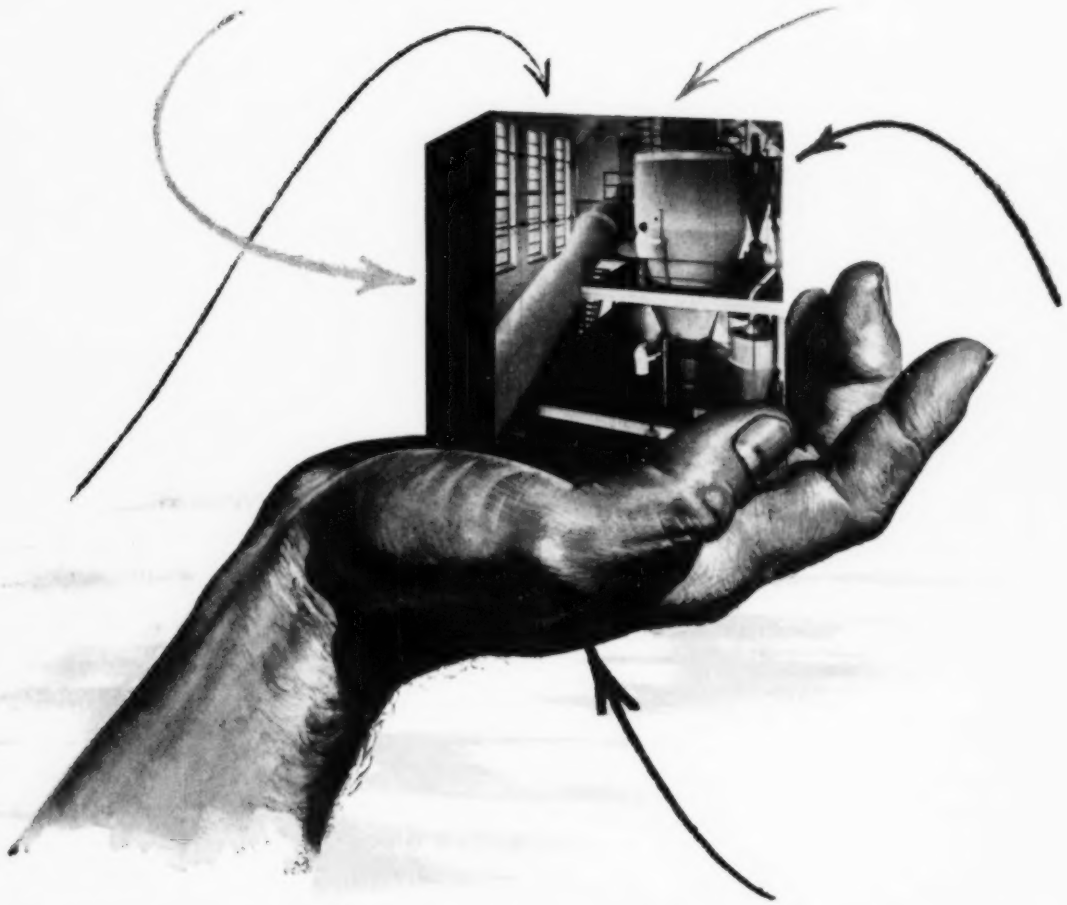

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